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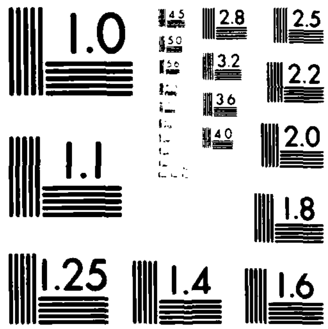
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FINAL REPORT

FUNDAMENTAL RESEARCH ON TRIBOLOGY

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to

The U.S. Army Research Office
Research Triangle Park
North Carolina 27709

under

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Final report of a three-year project pertaining to fundamental research on tribology. Topics investigated by an interdisciplinary team were: surface mechanics; studies of microscopic surface phenomena prior to microscopic changes; surface reaction kinetic studies related to wear processes; physico-chemical processes in the contact line region; thermal control of friction; fundamental study of solid lubrication in the SEM; lubricated sliding studies in the SEM; friction reduction in an I.C. engine; start-stop evaluation of

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) gas bearing materials; continuous wear measurement by on-line Ferrography; wear of copper-based brake material.

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1. INTRODUCTION

The U.S. Army Research Office undertook to fund the interdisciplinary program in 1979, under Contract DAAG29-79-C-0204, FUNDAMENTAL RESEARCH ON TRIBOLOGY, which was renewed under Contract DAAG29-83-K-0058.

This final report covers research conducted between 15 March 1983 through 16 May 1986. Section 2 discusses briefly the areas of achievement. Section 3 gives an account of the research team and interdisciplinary collaboration. In the space below, a renewed look at the need for tribology is made. It is axiomatic that the generic technology of tribology must be underpinned by fundamental research.

Tribology, the science and technology of friction-lubrication-wear, is vital to the design, manufacture and utilization of virtually every system with moving parts [1,2]. Its purpose is to optimize the energy efficiency, product durability and reliability of machines and systems.

It has been estimated by the National Commission on Materials Policy [3] that wear costs the U.S. economy 15 billion dollars a year in materials costs alone in 1973. In addition, a report "Strategy for Energy Conservation Through Tribology" [4] shows that up to an 11% saving in national energy consumption is possible from the direct or indirect benefits of an R & D plan consisting of some 40 specific projects dealing with friction, lubrication and wear of machine components. More recently, a closer estimate has been made of energy savings for the United States [5].

Japan, France, Germany, the UK, the USSR, among others, have redoubled their respective tribology research efforts since the beginning of the Army Research Office tribology project at Rensselaer. During 1981, a German report estimated the benefit to the USA to be $23,000,000,000 annually if tribology is vigorously pursued. Of course, this saving is possible only with some investment; the cost-benefit ratio in specific cases has been shown to be attractive indeed.

The wear control and friction problems in mechanical components generally determine energy efficiency, product durability and reliability of machinery, both simple and complex. These problems are usually of fundamental origin and research on them can have lasting impact on both technology and manpower preparation. The machines in which wear control is needed are of immediate importance to the effectiveness of our nation's defense missions as well as to our industrial community in general. Thus, the program elements proposed here may solve immediate field problems associated with performance effectiveness, equipment availability (readiness), and reliability, while also providing an effective advance in our fundamental technology base. It is also very clear that advances in tribology can mitigate our national concerns for conservation of energy and materials of machine construction.

Rensselaer is a recognized center for advanced research, development and education in tribology; it is the only university in the United States offering a degree program in tribology. That multifaceted interdisciplinary technology requires a diversity and intensity of expertise not usually found in a single organization but which is available in the Institute for Wear Control Research (IWCR) functional laboratories and affiliated laboratories to be detailed later.

Eminent scientific expertise and capable graduate students are available to pursue these investigations in the established laboratory facilities.

Rensselaer has been associated for a quarter of a century with the field now covered by tribology. During that period, there have been many significant advances to the field attributable to activities here. Recently, under the formal structure of IWCR, significant problems solved include: for the MAB Metal Processing Equipment Program (MPEP), a major contribution won the French Joseph Marie Jacquard Medal, Groupement pour l'Advancement de la Mechanique Industrielle for Professor Ling; the DOT sponsored Coast Guard icebreaker hull coating study has resulted in an RPI certified coating which has demonstrated a dramatic increase in abrasion life over conventional coatings and has also shown considerable reduction of ship drag losses; the Caterpillar Tractor Company sponsored effort on cavitation erosion of bearing materials in the D-10 tractor diesel engine has broken new ground in understanding premature failures of new bearing materials; the NASA sponsored aircraft brake program has resulted in new materials and/or new designs for high energy brakes for the future. New advancements in the understanding of surface of materials and coatings have recently been achieved; these include tentative failure modes of surfaces in sliding contact.

2. RESEARCH ACHIEVEMENTS

2.1 Long-Term Goal

To improve the quantitative and fundamental understanding of wear processes relevant to mechanical components which represent advancement as to improved mechanical reliability, energy efficiency and critical material substitutability.

2.2 Near-Term Goal

To conduct research on tribology on broad fronts which are relevant to the quantitative and fundamental understanding of wear in boundary and microelastohydrodynamic lubricated systems, and with boundary lubricated material parts which are primarily composite systems.

2.3 Research Achievements

2.3.1 Surface Mechanics.

Surface mechanics as an area of endeavor was coined over a decade ago to stress the importance of modeling surface related phenomena and to provide the ingredients for contact problem formulation [6] in what is now known as the field of tribology [3].

History has shown that contact mechanics in general have been the subject of inquiry since the last century. But a subset, which is of contemporary technical relevance, has only been treated in the literature more recently. The subset is characterized by moving references, the use of transform techniques, single layered media and generic solutions whenever possible. It should be noted that the singleness of layer is not limiting in light of the availability of numerical inversion via transform algorithms [7]. Examples are surface temperatures under moving heat sources: under the high speed approximation of the relevant heat conduction equation, cases studied were the cases of a layered half space, a layered circular cylinder and a layered sphere [8]. Next is a pair of problems with surface load on a layered half space in the case of elastic layer [9] and in the case of viscoelastic layer exhibiting standard linear model [10]. Moreover, human joint cartilage has been modelled as a layered media [11]. Within the definition of surface mechanics, Professor Ling, various graduate students, and colleagues have been examining the effects of several field interactions, of nonlinearities, of anisotropy and of environments on surfaces. In the space below, the work of doctoral student Mary Dawson, under Professor Ling's direction, will be discussed in some detail.

The relevance of surface roughness range from the loading of mating surfaces and their response [12,13,14,15,16] to frictional behavior at high pressure [17], from changes of surface roughness during running-in of machine elements [18] to the roughness of surfaces as they are manufactured [19] and examined [20].

The significance of the mechanics of surfaces has been shown [6] and the importance of surface texture of solids has been reiterated recently [21].

Much of surface roughness effort was pioneered by Greenwood and Williamson [15] who established a criterion for distinguishing asperities which contact elastically from those deforming in the plastic range. This led to the development of a parameter which they termed the Plasticity Index. Peklenik [22] expanded on this approach by introducing statistical methods of random process analysis to eliminate many of the simplifying assumptions. He pointed out that a statistical characterization of the surface in any one direction can be obtained by determining the autocorrelation function of the profile or the related power spectrum. Whitehouse and Archard [23] used this concept to characterize a model surface by two parameters: σ, the standard deviation of the height distribution, and β^*, the correlation distance (i.e., the distance at which the autocorrelation function takes the value 1/e). They then showed that the surfaces can be characterized in terms of σ and β^* and that the plasticity index can also be expressed in these terms.

Although many refinements have been made in these approaches (e.g., [24]), most of the effort has been analytical in nature. One exception is the experimental work of Hirst and Hollander [25] who ran lubricated, single-pass tests using a stainless steel ball sliding against steel flats with various surface textures. A solution of 1% stearic acid in white oil served as the lubricant. They found that the transition temperature was high when plastic deformation was limited to the surface asperities and the bulk stresses in the stainless steel were within the elastic limit. When bulk plastic flow occurred, the transition temperature was much lower. Figure 1 summarizes the results of their tests and shows safe and unsafe regions of operation. One very significant point was their finding that highly polished surfaces failed consistently. This bears out the experience that was described previously on superfinished bearing surfaces.

Despite the importance of the work done by Hirst and Hollander, follow-on efforts are lacking. There is a need to expand this type of study to include other material combinations and surface geometries.

Recognizing the significance of this avenue of endeavor, the Tribology Laboratory at Rensselaer has established an on-going program to characterize various tribological surfaces that are being used in industry. These are typically high precision components such as aircraft rolling contact bearings and computer recording discs. The laboratory surface profilometer has been coupled through an A/D converter into a mini-computer, and appropriate software programs have been written to calculate a variety of surface texture parameters. During the current contract term, new insights have been added to the understanding of the phenomenon first advanced by Hirst and Hollander.

The scuff-limited load capacity of both hardened and annealed AISI 52100 steel balls sliding against hardened carbon steel flats was investigated [26]. Silicone oils were used as the lubricants. The test flats were prepared by directional grinding to $\sim$250 mm arithmatic average surface height, the abrading with various grades of abrasive paper. When tested in methylphenyl silicone oil, asground flats exhibited the highest load capacity--the smoothest flats, finished on a metallographic polishing wheel with 600-grit abrasive, the lowest. As the flats ran in, the root mean

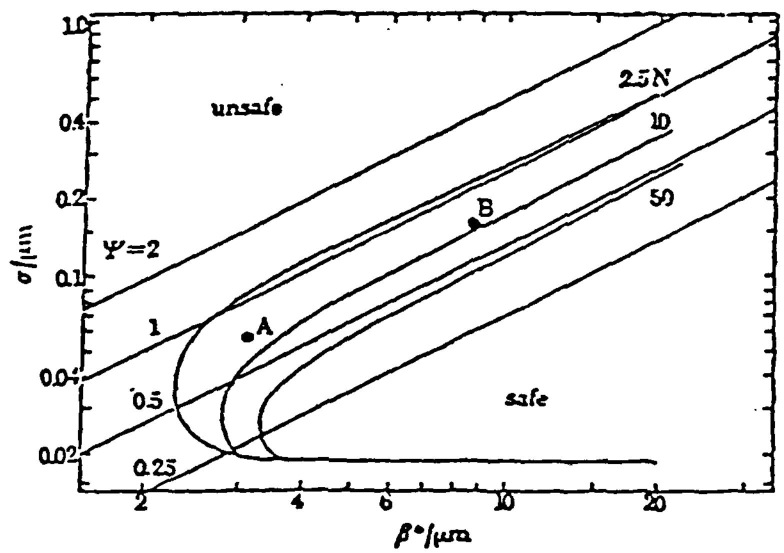


Figure 1. σ − β* Map for Abraded Surfaces Showing Lines of Constant Ψ (Plasticity Index), and Boundaries Between Safe and Unsafe Regions. (Taken from Ref.[15]).

σ = Height distribution
β* = Autocorrelation function

Note: When β* becomes small, the range of σ which is "safe" diminishes. Below a β*-value of about 2 μm, no surface would support any significant load.

square surface asperity height, Rq, decreased and β^*, autocorrelation distance, increased such that the surface "moved" in the Rq-β^* plane. The "motion" is approximately perpendicular to lines of constant ψ, which is the so-called plasticity index. Among other conclusions, failure occurred when ψ reached a value of $\sim$0.01, regardless of initial surface topography.

The importance of surface texture in solid film lubrication is still poorly understood. Early work on solid lubricant films showed that roughening of the surface of ferrous alloys, prior to coating, was one essential step in providing good adherence and film durability. Although subsequent work [e.g. 27] has confirmed and refined those results to some extent, there still does not appear to be a good consensus as to the best method for surface preparation, or a good specification of what the optimum substrate and counterface textures should be. Average surface roughness is the only criterion presently being used. It is generally hypothesized that mechanical or chemical roughening of the surfaces forms pockets that act as reservoirs to provide fresh lubricant as the surface layer is worn away [28]. However, recent experience with very thin, sputtered coatings of solid lubricants on relatively smooth substrates appears to contradict this concept that roughened substrates are essential for long life. In many cases, the sputtered films are much more durable. The situation is further complicated by the fact that the chemical composition of the substrate also affects the adherence of the solid film lubricant.

The problem of optimizing surface texture will become increasingly important because of the interest in the use of solid lubricants for tribological components made of ceramic-type materials. Much care is now taken to produce as good a finish as possible on these very hard materials. If it is then necessary to roughen the surfaces in order to improve lubricant life, it would be very difficult to do this in a controlled manner.

To date, combined experimental observations and modelling studies are being undertaken to define which topographical features have the greatest influence on lubricant life. Two widely different metallic alloys (steel and aluminum) and two ceramic materials (Al_2O_3 and SiC), are being used as the substrates. These choices make it possible to isolate chemical from mechanical effects.

2.3.2. Studies of Microscopic Surface Phenomena Prior to Macroscopic Changes. Although lubrication has been recognized as a surface phenomenon for a very long time and is of enormous importance in modern civilian and military technology, the changes occurring on a microscale which must precede macroscopic changes, such as failure by scuffing, are still mostly unknown. Professor Lauer's work has been in the discovery of microscopic changes. His prime tool has been infrared emission Fourier microspectrophotometry, an infrared Fourier spectrophotometer coupled to a microscope. Improved over many years, this instrument is now capable of analyzing lubricant layers only 10 Å thick or even less with a spatial resolution of 10 μm. Since the detector is liquid nitrogen-cooled, even room temperature samples can be analyzed with sufficient shielding. Other instruments in Professor Lauer's Laboratory of Boundary Layer Analysis are (i) a phase-locked interference microscope (PLIM), an electronic Faraday effect-modulated ellipsometer of high spatial resolution (FEME) and apparatus to determine lubricant film thickness optically in elastohydrodynamic contacts. All of this instrumentation is applicable to measurements through windows in operating bearings.

During the current contract period various studies have been made. Bearing surfaces of M-50 steel were operated for different periods of time with varying parameters on a number of lubricating oils and additives, such as tricresyl phosphate (TCP) antiwear agent, amine anticorrosive agents and antioxidants. Optical surface profiles were obtained with the PLIM to a depth resolution of ± 30 Å for 10 μm diameter areas within and outside the wear track. The optical constants and film thicknesses were obtained with the FEME with the same spatial resolution. The most significant results of this study were the formation of Fe_3O_4 in patches within the wear track when TCP was present in the lubricant while otherwise Fe_2O_3 was the main oxide. In general, metal oxide formation was accelerated within the wear track. This work was the subject of a paper presented at the International Tribology Conference in Tokyo [29].

TCP also reduced the high frequency surface roughness, thereby reducing wear. The latter effect is also produced by ion implantation. Fe_3O_4 causes less wear than Fe_2O_3. Auger electron spectroscopy (AES) under high vacuum was carried out by Professor Hudson on some of the same samples and confirmed the results wherever pertinent. The advantage of the FEME is its applicability under operating and atmospheric conditions [29,30] while AES requires ultra-high vacuum and may be destructive.

Infrared emission was proved indeed to be as Hordvik [31] and others have claimed, "the technique with the greatest potential for measuring low loss and, at the same time, providing spectral information." Since emissivity is always obtained with reference to a blackbody emitter at the sample temperature, a temperature measurement is an unavoidable by-product of the technique. Furthermore, as the emittance of thin layers should be directly proportional to their thickness [32], suitable calibration procedures should provide thickness data. However, when these principles are applied to thin layers on metal surfaces, complications show up which must be accounted for if reliable information is to be extracted. These factors involve the reflectance at both surfaces bounding the layer, the image dipole apparently within the metal, interference between directly emitted and reflected radiation, reabsorption of emitted radiation within the layer, and physical orientation of the layer itself. Greenler [33], Makinouchi, Wagatsumi, and Suetaka [34], and Hvistendahl, Rytter and Oye [35], among others, called attention to these phenomena, but no systematic procedure was developed for sorting them out to get at data under realistic conditions.

A study was undertaken to obtain the spectral information necessary for the extraction of the required data. Theoretical analysis formed the basis of a computer program for the determinations. This analysis showed the need for collecting emission spectra at certain angles with the optic axis of layers of known materials of known thicknesses on well-characterized metallic surfaces in order to carry out calibrations. Experimentally this task was accomplished by obtaining the spectra of the materials to be determined from the emission spectra of substrates containing these materials (oils) in different known concentrations as well as the spectra of the pure oils on these surfaces. Including the oils in substrates removes the orientation or polarization factor from some of the spectral bands. These substrates were applied in known thicknesses to smooth metal plates which, in turn, were brought to constant elevated temperatures so that the infrared radiation emitted could be analyzed. Spectra were obtained with a modified commercial infrared Fourier spectrophotometer [36].

The polarization effects in the spectra can be made use of in the determination of the thickness of dielectric layers (e.g. oxides) interposed between a metal surface and a lubricant adsorbate.

Interest in the infrared emission microscope-spectrophotometer accessory led not only to a publication at an international conference [37] but to many requests for a commercially available unit. Harrick Scientific Company of Ossining, NY, has agreed to manufacture it.

Another study concerns deposits laid down in patches on metal strips in a high pressure/high temperature fuel system simulator operated with aerated fuel at varying flow rates. These patches were analyzed by emission Fourier Transform Infrared (FTIR) in terms of functional groups. Significant differences were found in the spectra and amounts of deposits derived from fuels to which small concentrations of oxygen-, nitrogen-, or sulfur-containing heterocyclics or metal naphthenates had been added. The spectra of deposits generated on strips by heating fuels and air in a closed container were very different from those of the flowing fluid deposits. One such closed-container dodecane deposit on silver gave a strong surface enhanced Raman spectrum [38,39]. The deposition rates of these materials follow diffusion mechanisms with abrupt changes. At the same time, their composition, primarily with respect to oxygen-containing functional groups, also changes.

The lubrication aspect of this study on fuels was the pumpability, which is strongly influenced by the presence of trace amounts of non-hydrocarbons. These materials help provide "lubricity," by providing surface coatings or deposits resembling the friction polymers of lubricants.

2.3.3. Surface Reaction Kinetic Studies Related to Wear Processes. This program, being carried out by Professor Hudson and his students, involves both basic and applied studies of chemical reactions that can take place in a wear environment.

Applied studies carried out to date include an investigation of material transfer in silver-plated copper electrical contacts, in which Auger electron spectroscopy (AES) was used to measure the flow of the plating over the substrate, and the eventual contact failure of wiping transfer of base metal from the contact edge over the silver surface.

More recently, scanning Auger microscopy (SAM) has been used to determine near-surface composition changes that take place during the wear process. In this study pure iron samples were run in a pin on-disc configuration in a variety of lubricants. It was generally found that the most severely worn portion of the sample contained significant concentrations of dissolved carbon. Less severely worn regions showed increased concentrations of both carbon and oxygen. In addition, samples run in fluorocarbon lubricants showed significant fluorine uptake. The edge of the worn area showed primarily carbon in a non-dissolved form, some oxygen and, for fluorocarbon lubricants, some fluorine. This region probably consisted of "friction polymers arising from partial decomposition of the lubricant.

A major basic investigation involved characterization of the interaction of acetylene (C_2H_2) with the Fe(110) surface [40]. This system was chosen as a prototype of hydrocarbon lubricant interactions with transition metal alloy wear surfaces. Previous studies of this system, using such techniques as ultraviolet photoelectron spectroscopy (UPS) [41], low energy electron diffraction (LEED) [42], electron energy loss spectroscopy (EELS) [43] and temperature programmed desorption (TPD) [42,43] provided a qualitative picture of the interaction process, but gave no information on the rates or the basic mechanism of the surface processes involved.

In our work, the adsorption, decomposition and bulk uptake sequence was studied using molecular beam relaxation spectroscopy (MBRS) and Auger electron spectroscopy (AES). Because of artifacts introduced by interaction of the probing electron beam with the surface species, AES was used only for qualitative characterization of the reaction process. An extension of the previously-developed techniques for the analysis of MBRS data to the case where the mean surface coverage is increasing with time was developed and applied to acetylene scattering data obtained as a function of acetylene adlayer coverage. Results indicated that adsorption takes place through a weakly-bound precursor state. Dissociative and non-dissociative adsorption take place simultaneously in the temperature range from 300-600K, with dissociation being increasingly favored at higher temperatures. At the high end of this range, dehydrogenation of the adsorbed CH fragments takes place, and at still higher temperatures the resulting adsorbed carbon dissolves in the bulk of the sample. These results are reported in greater detail in reference [44].

2.3.4 Physicochemical Processes in the Contact Line Region. An understanding of physicochemical processes (wetting and transport processes) in ultra-thin films ($\delta < 10^{-5}$ m) and in the contact line region ($\delta \to 0$) is important to good lubrication. These processes should be optimized to promote film stability and heat transfer, and to minimize frictional losses. The processes are controlled by a gradient in the chemical potential which is a function of temperature, composition and film thickness. In these thin film systems, interfacial effects are magnified and a small amount of a second component can cause dramatic changes in wetting and in the transport processes. Experimental results have demonstrated that these changes have a dramatic effect on lubrication. Therefore, a systematic study of the effect of changes in the bulk composition on wetting and transport processes in nonisothermal ultra-thin films has been conducted during the current contract period by Professor P. C. Wayner and his students.

It has been proposed that since the chemical potential of a curved film is a function of the film profile, concentration and temperature, considerable information concerning the physicochemical processes in a thin film could be obtained by studying the effect of evaporation on the profile of a stationary evaporating film. To demonstrate the validity of this hypothesis, a heat transfer cell with a scanning microphotometer capable of studying evaporating ultra-thin films was developed and tested at Rensselaer [45-48]. The results of these studies demonstrated that the experimental equipment was capable of generating extensive detailed information on wetting and the transport processes occurring in the film thickness region $\delta < 10^{5}$ m. Briefly, a series of experiments using various alkanes demonstrated that a stationary evaporating film is stabilized by multicomponent adsorption, a curvature gradient, a disjoining pressure gradient and surface shear stresses that are a function of the temperature gradient and solid-fluid system. Comparison of the single component results with those obtained using a mixture demonstrated that the addition of a small amount of a second component with a lower vapor pressure gave a significant increase in stability at the same temperature.

In a set of theoretical publications, various models for the transport processes in evaporating films in the region $\delta < 10^{-5}$ m have been presented [49-51]. The following equation for the mass flow rate in an evaporating film delineate the various mechanisms causing bulk flow [49-51]. Diffusion is treated as a second order effect in this model.

$$\Gamma = \frac{\delta^3}{3\nu}\left[\underset{(I)}{1.5\delta^{-1}\sigma'} + \underset{(II)}{\delta^{-n}B'} + \underset{(III)}{K\sigma'} + \underset{(IV)}{\sigma K'} - \underset{(V)}{nB\delta^{-(n+1)}\delta'} - \underset{(VI)}{\rho g\delta'\cos\theta} + \underset{(VII)}{\rho g\sin\theta}\right] \quad (1)$$

where

Γ = mass flow rate in thin film

δ = film thickness

σ = surface tension

B = dispersion constant

θ = angle of inclination

K = curvature

ρ = density

g = gravitational constant

h_{fg} = heat of vaporization

The important terms in (1) are identified as follows:

$\sigma K' + K\sigma'$: Capillary Pressure Gradient

$\frac{B'}{\delta^n} - \frac{nB\delta'}{\delta^{n+1}}$ "Disjoining Pressure" Gradient

$\frac{\sigma'}{\delta}$ Surface Force/Volume

The prime refers to differentiation with respect to position, x. The product $\Gamma' h_{fg}$ gives the heat flux in cooling. In this equation Terms (I-III) are functions of the temperature and concentration variation along the interface, whereas Terms (IV-VII) are functions of the film profile. The dispersion constant B accounts for adsorption effects whereas the surface tension accounts for effects at the liquid-vapor interface. The significance of the last finding is that additional insights concerning the conditions under which Terms (I-III) are important were developed [51]. The results demonstrated that the effect of surface shear on fluid flow can change sign in a "distilling" thin film as it flows towards the heat source along a constant vapor pressure line when $\sigma_2 > \sigma_1$ (subscript 2 refers to the less volatile component of a binary mixture). Assuming that the flow starts in a region where surface shear enhances the flow towards the heat source (with surface tension a function of both temperature and pressure) a composition is reached in the flowing film at which flow reversal can occur in the film. The location of the sign reversal is a function of the concentration, the temperature level, and the difference in the surface tensions of the components of the binary mixture. Now sufficient insight is available to model all the bulk flow effects. At the current level of development, molecular diffusion is neglected because it is relatively less important.

2.3.5 Thermal Control of Friction. Professor C. M. McC. Ettles joined the project as of 15 March 1985. What follows are his current activities as well as those proposed for the future.

A recent study has shown that friction in dry sliding could be computed as a dependent parameter when the contact conditions are either moderate or severe. The analysis was based on the assumption that for two different materials in contact, surface temperatures greater than the least of the two decomposition temperatures cannot be generated, since as soon as the lowest decomposition temperature is achieved the material is removed from the contact.

The model has been set up both numerically and analytically. The numerical scheme allows detailed configurations to be considered with arbitrary geometry, transient conditions and the coupling of thermal properties with temperature or pressure. The model gives detailed solutions of particular cases, although generality is lost. However, generality is retained in the analytic solution, which is in closed form.

The model has been shown to be reasonably effective in computing the friction of rotating bands in large caliber guns [52], tires on pavement [53], and more general contacts of polymers, metals and ice in various combinations [54]. Improvements to the numerical model and comparison against further experimental results in the literature are being carried out. Specific improvements and extensions include the following:

- The basis of the thermal analysis are being changed from a control volume discretization to a four noded quadrilateral finite element scheme. Thermoelasticity can then be included using the same elements as the thermal analysis.
- The effect of thin overlays of various metals in reducing friction are assessed for such configurations as rotating bands and sliding armatures in electromagnetic launchers.
- A consideration of tire friction [53] suggests that skidding resistance can be increased by the use of aluminum swarf as a filler in the tread material.
- A first attempt are being made to develop a quantitative model of wear based on thermodynamic principles.

2.3.6 Fundamental Study of Solid Lubrication in the SEM. The development of the scanning electron microscope (SEM) has provided scientists and engineers with a powerful tool for viewing the physical features of surfaces. High-magnification observations can be made with full-field sharpness because depth of field limitations are less of a problem than with optical microscopes. Recent improvements in the design of these microscopes, particularly the increased size of the working area in the microscope chamber, have enhanced the possibility of conducting and simultaneously observing the progress of dynamic experiments within the chamber. For example, many models now feature optional accessories for tensile tests. A logical extension of this experimental capability was the development of a sliding test rig that could also be run in the microscope chamber. Buckley [55] described one such test device that was built at the NASA Lewis Research Center. Experiments using a diamond penetrator were reported by Bates et al [56]. Glaeser [57] described the condition of a wear track after several passes of a steel ball in the same track. Kayaba and Kato [58] ran tests in the SEM while making successive observations on the removal of a single asperity due to adhesive wear.

A sliding test rig, similar to the one described by Buckley [55] was built by the Tribology Laboratory at Rensselaer. The primary reason for conducting these studies was to determine the effect of the metallurgical microstructures of various alloys on sliding performance, particularly surface damage and wear.

Of the observations that were made during this study, the most significant is considered to be the fact that wear debris was in the form of thin platelets [59]. These platelets were produced by shear forces which tended to move the material as thin laminations, analogous to the way a deck of cards would separate when subjected to both normal and shear forces. This was the case, regardless of the metallurgical structure or phases present in the alloys. Even though a hardened stainless steel pin sliding against precipitation-hardened stainless steel formed wear particles in elongated stringer form, rather than platelets, the stringers still appeared to have a thin cross section. Admittedly, the low sliding velocity, absence of a lubricant film, and the high initial stress all influenced this wear behavior, but this basic mode of wear also seems to predominate in lubricated sliding as demonstrated by wear particle examination in ferrography [60]. Fatigue has been proposed as one mechanism for the production of laminar wear particles [61]; however, this could not be a factor here since the number of stress reversals are so low. The production of these thin platelets of wear debris commences very early in the test, during the first revolution of the cylinder.

The formation and direction of crack fronts in the disturbed material ahead of the slider is a phenomenon that also deserves more study. The characteristics of the crack fronts appear to be influenced by the strength and/or metallurgical structure of the materials. With mild steel specimens, the crack progresses ahead of the pin and parallel to the direction of sliding. With hardened 1095 steel sliding on hardened martensitic stainless, major cracks form perpendicular to the direction of sliding and progress around the pin.

It is important to note that grain boundaries do not seem to influence the wear process. Microcrack progression appears to be both intergranular and transgranular.

The formation of wear particles was consistently dominated by deformation of the matrix microstructure. Even those materials which contained hard particles in the structure (e.g., carbides in heat-treated steel) wore because of matrix deformation. The carbides did not seem to contribute to the results except, possibly, for a change in the direction of the crack front.

For the case of a soft pin material, such as brass, sliding against a hard surface, considerable transfer of brass was observed in the form of islands. The location of this transfer did not appear to be selective as far as the structure of the steel surface was concerned. It was evident on different phases and even on carbides. Based on the observations made from these tests, the following conclusions can be made:

- o Wear particle removal always appears to be in platelet form.
- o Grain boundaries have no effect during the wear process.
- o The removal of wear particles is always caused by deformation of the structure adjacent to the carbides.
- o Microstructural features such as grain boundaries and carbides are not visible on the back side of the particles as they are removed from the surface. The underside of the wear particles are very smooth and have no physical features which might indicate their makeup.
- o Crack propagation due to sliding can be parallel to the direction of sliding for some materials and perpendicular for others.

2.3.7 Lubricated Sliding Studies in the SEM. Modifications have been made to allow use of the Tribology Laboratory's scanning electron microscope to observe the study liquid lubricated surfaces. The approach involves isolating the SEM column and chamber and using a separate vacuum pumping system to keep the chamber at a higher pressure relative to the column. The higher chamber pressure (approximately .1 Torr) results in reduced outgassing and charging of the liquid lubricant.

Preliminary work with thin lubricant films is currently in progress. For example, a typical photomicrograph showing a thin film of Apiezon N grease on a ground steel surface is shown in Figure 2. In the darker areas of the photomicrograph, a relatively thick layer of grease is covering the surface and attenuating the electron signal. Note, however, that the steel surface is being imaged through the grease film and is clearly visible beneath it.

Fundamental liquid lubricated sliding experiments performed inside the SEM are being carried out to augment dry-sliding and solid-lubricated

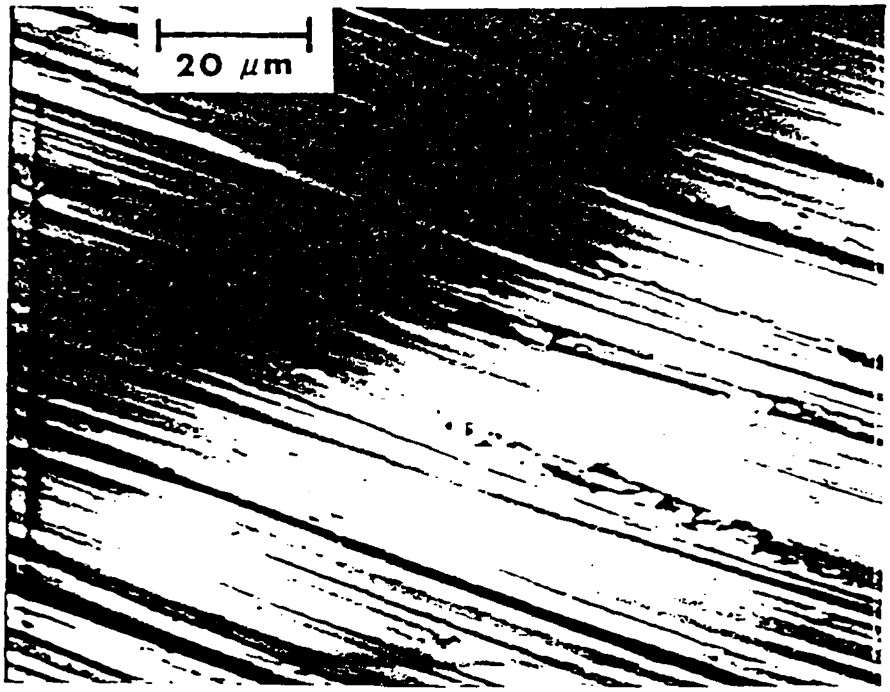


Figure 2. SEM Photomicrograph of a Ground Steel Surface Being Imaged Through a Film of Apiezon N Grease. (Magnification 1000 ×)

studies already in progress at Rensselaer. Specifically, studies involve the effect of a very thin liquid film on the specimen surface. Simple lubricants and fundamental hydrocarbon fluids such as Apiezon lubricants or cetane are used.

2.3.8 Friction Reduction in an I.C. Engine. This effort, which is done in conjunction with Dr. J. Fodor of the Hungarian Research Institute of Automotive Industry, is complete. In brief, friction and wear losses of a 6-cylinder i.c. engine were determined as a function of the engine's cleanliness [62]. The engine cleanliness was controlled by highly improved air and lubricant filtration. The engine was driven externally and therefore operated without combustion. Friction was measured by means of a weight balance, and wear was measured by both ferrography and gamma-ray spectrometry of neutron-activated wear debris.

These types of filtration were used: the normal filtration (the usual engine oil filtration), the super-fine (SF) filtration, and the SSF filtration. Oil purity was found to be 0.016%, 0.005% and 0.0025% for the three filtration methods respectively. The average friction pressure was changed from 171.8 kPa to 166.8 kPa, as a consequence of the oil purity level control by the filtration.

With a patented, chelate type metal organic compound, friction was reduced to 162.5 kPa. Considerable wear reduction was also achieved.

2.3.9 Start-Stop Evaluation of Gas Bearing Materials. This activity [63] has been completed.

In the study several material combinations were evaluated as gas-lubricated bearings in a hydrodynamic journal bearing test stand. The objective was to compare their performance under start-stop conditions at various stress levels in a helium environment. Some of the tests were run at 296K and others were run at 77K. To detect gradual changes in performance, measurements of torque and the time required for coastdown as well as periodic surface examination (visual and surface profilometry) were made.

At room temperature, bearings with aluminum substrates, anodized aluminum sliding against either electro mickel or tungsten carbide gave the most promising results. Anodized aluminum against chrome carbide was a close second.

At low temperatures, only nitrided steel sliding against itself was a viable combination.

2.3.10 Continuous Wear Measurement by On-Line Ferrography. This activity [64] has been completed.

In this study are on-line Ferrograph was used to monitor the wear rates of oil lubricated ball bearings. Periodically, the test bearings were removed from the test stand and cleaned and weighed on an analytical balance. A comparison of the mass loss data obtained by each of these two methods showed that the Ferrograph readings did provide on-line quantitative wear data for each individual test. However, the correlation between Ferrograph readings and wear data could vary from test to test. For the four ball bearings that were evaluated, plots of the Ferrograph concentration readings versus bearing mass loss gave slopes that varied between 1.1 and 2.5. Nevertheless, the results showed that semiquantitative data on wear rates of machine components could be obtained with this on-line instrumentation.

2.3.11 Wear of Copper-Based Brake Material. This effort has been completed [55]. In an earlier, comprehensive study at Rensselaer of copper-based brake material sliding against 1722-AS steel, as used in aircraft, it was concluded that the wear, w, of brake material was proportional to surface temperature relative to the melting point of copper, Tm, and that it obeys the empirical relationship,

$$\Delta w = kT/(T_m - T),$$

where k is a constant.

This study re-examined the original data and reported on a new finding. That is, the wear rate, $\overset{o}{w}$, of the brake material obeys, at elevated temperatures, a similar relationship,

$$\overset{o}{w} = kT/(T_s - T),$$

where T_s is the temperature at which micro-hardness first vanishes. Moreover, the relationship appears to be consistent with Holm's wear theory.

3. THE RESEARCH TEAM AND INTERDISCIPLINARY COLLABORATION

3.1 Principal Investigator

The principal investigator is Frederick F. Ling, Director of the Institute for Wear Control Research.

3.2 Senior Investigators

Senior investigators represent an interdisciplinary team as follows:

James L. Lauer	Research Professor of Mechanical Engineering and Director, Laboratory for Boundary Layer Analysis
Sydney Ross	Professor of Chemistry and Director, Colloid and Interface Science Laboratory
John B. Hudson	Professor of Materials Engineering and Director, Surface Studies Laboratory

Peter C. Wayner	Professor of Chemical Engineering and Director, Interfacial Transport Processes Laboratory
Christopher M.M. Ettles	Associate Professor of Mechanical Engineering

3.3 Research Staff and Assistants

On the staff of the Institute for Wear Control Research (IWCR) are:

S. Frank Murray	Senior Research Engineer and Manager, Tribology Laboratory
Salvadore J. Calabrese	Research Specialist

Ph.D. bound graduate assistants have been selected from each discipline. Selected for their superior qualifications and supported on the full time basis are Mary C. Dawson (nee Herbert), who graduated first in her class, held two fellowships during her M.S. studies, worked at the General Electric Company before returning for her doctoral studies and Wolfgang Holzhauer, who graduated near the top of his class and studied abroad during his junior year at the Swiss Federal Institute of Technology.

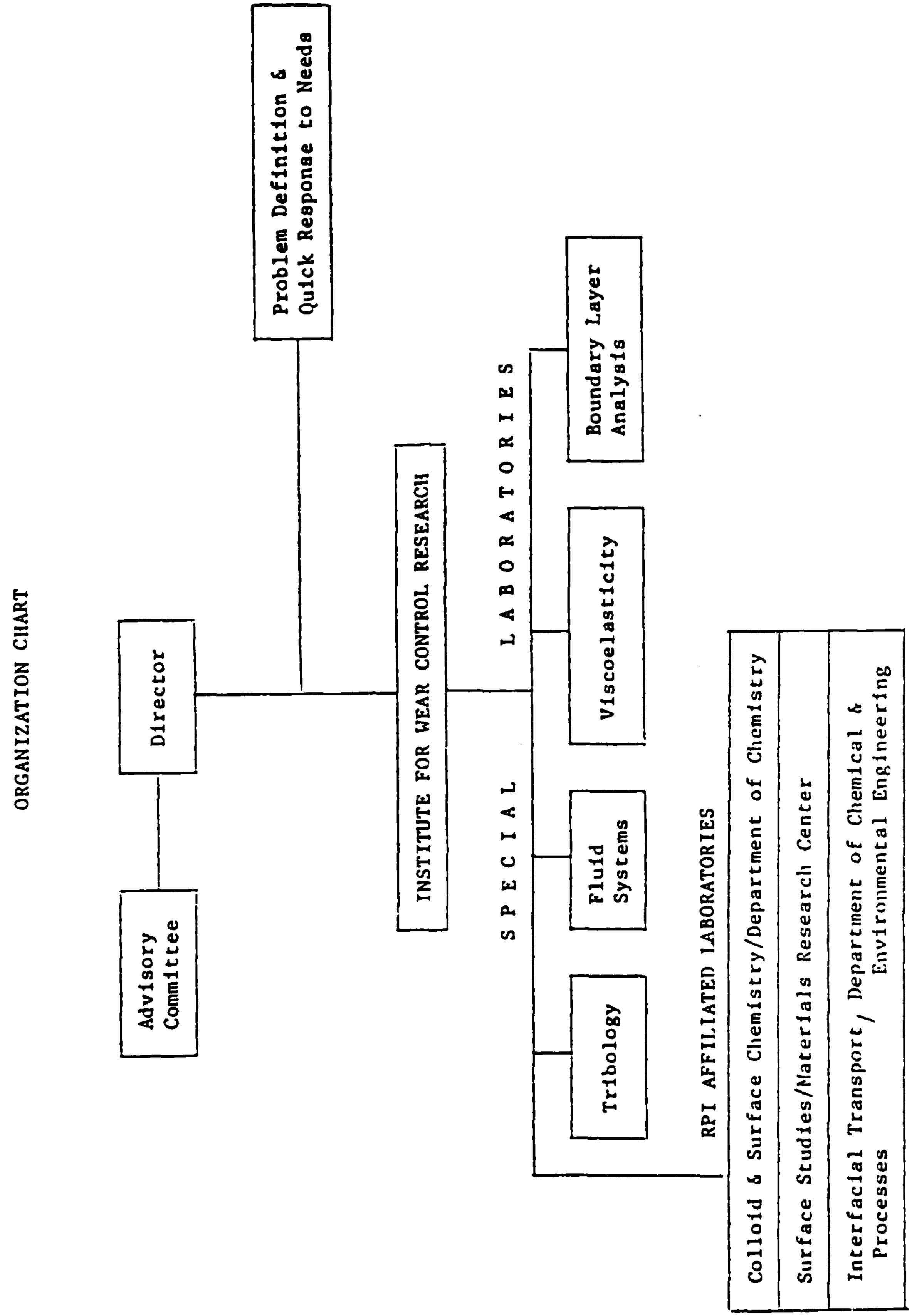
3.4 Monthly Tutorial/Area Specialty Seminars

Monthly Tutorial/Area Specialty Seminars have been held. These are occasions, about two hours in duration, when members of the investigative team (faculty and/or graduate students and/or staff) survey their areas and report their latest findings. Various members do this by rotation; occasionally a guest participant is asked to join in to enrich the discussions.

3.5 ARO Panel Review Meetings

Annual meetings have been held when the Rensselaer team would review project progress for the ARO Panel.

3.6 Institute for Wear Control Research (IWCR) and Its Functional Laboratories



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