RESEARCH NEEDS AND OPPORTUNITIES IN THE AREA OF FRICTION AND SYSTEM DYNAMICS

Part II

Report of the Workshop on the Interaction of Friction
and System Dynamics
June 20 - 23, 1997

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SUMMARY

A wide variety of friction related phenomena at sliding interfaces influence the dynamical response of mechanical systems. The understanding of these phenomena and their coupling to mechanical assemblies are poorly understood and yet have enormous consequences. A workshop held over the period June 20-23, 1997 defined a number of microscopic interfacial phenomena that contribute to these large scale dynamic responses. These phenomena themselves are not completely understood, however, by developing a microscopic understanding and theory that can be scaled up to the macroscopic level it was felt that global models could be developed for predicting the effects of friction in moving mechanical assemblies. It was recognized that as an important element of the scale-up one must consider both the influence of friction on system dynamics and the effect of system dynamics on friction. Empirically-based models are considered to be useful for the range of parameters over which they are obtained and, generally, may not be extrapolated to outside of their range. Further difficulty with empirical models is associated with repeatability of measurements which, in part, stems from dynamic behavior of the measurement set ups. These issues were discussed in the specific context of brake applications and a series of recommendations were made concerning the type and level of modeling that is needed to further our understanding of the coupling between friction and system dynamics.

1. PREFACE

This report summarizes discussions that occurred during the second, National Science Foundation-sponsored Workshop on the Interaction of Friction and System Dynamics. The Workshop was organized by the American Society of Mechanical Engineers and held from June 20 - 23, 1997 at the Shawmut Ocean Resort and Conference Center in Kennebunkport, Maine. Its purpose was:

> *to bring together a small number of experts from such areas as tribology, physics, chemistry, continuum mechanics, dynamics and vibrations, and materials to focus on specific research needs that will assist industry to predict the interactive nature of system response and interface behavior*.

This workshop was recommended in the report of the first workshop that was held in Pittsburgh, Pennsylvania during August 8 - 9, 1994. Accordingly, this second workshop brought together a team of seven experts from academia, industry, and government who possessed a broad range of knowledge and experiences in the technical areas listed above. A list of the panel members can be found in the Appendix.

2. INTRODUCTION

Building on the Results of the Previous Workshop

A workshop was held on August 8 - 9, 1994 to investigate the importance to industry of friction and system dynamics and to identify potential areas of research that could ameliorate some of the problems that such interactions can raise [1]. More than 50 people from industry and academia as well as from government agencies and laboratories participated in the 1994 workshop. Working together, these participants successfully identified major industries that are affected by this specific subset of friction-related problems, drew up a list of devices and processes that are most severely affected, and identified numerous practical impact areas in which research is required.

Participants in the 1994 workshop underlined the economic significance of friction to American industry -- costing billions of dollars each year. Likewise they concurred that there is no swift and simple way of describing (modeling) the interaction of friction and system dynamics. Nor is there a quick and easy way to obtain fundamental information needed to understand and control these interactions. Finally, they concluded that the necessary insights could not be expected to arise from continued independent efforts in any one discipline. It was clear that the time had come for a focused and coordinated, multidisciplinary research effort. However, time limitations did not allow the participants to develop the necessary plan for implementation of such a research program.

Structure of the Current Workshop

In the 1997 workshop, a small number of individuals were invited on the basis of their ability to represent the most critical disciplines and application areas. (See the preface for a list of participants.) Having a small number of participants allowed in-depth discussion and debate on key areas. The workshop agenda provided for the identification of :

- a critical application that could be explored in depth (brakes),
- the most relevant phenomena involved in determining the interaction of friction and system dynamics,
- research needed to better understand these phenomena and how they affect the interaction of friction and system dynamics,
- measurement capabilities needed to properly characterize these interactions,
- recommendations which, if implemented, could assist in better understanding and controlling the phenomena leading to interaction of friction and system dynamics.

3. GOALS AND OBJECTIVES

The goal of this workshop was to formulate a research agenda that would effectively address significant industrial problems involving the interaction of friction and system dynamics. The agenda, by necessity, covers, frictional phenomena over a broad range of length scales and time scales; it requires and integrates material properties, chemical phenomena, and others. The outcome of the workshop is a road map for research that will lead to verifiable, predictive models of friction in the context of system dynamics for real engineering system.

In this report we attempt to emphasize the effects of dynamics on those friction processes that are considered to be important in dynamic systems. As such, the recommendations from this workshop attempt to not duplicate those recommendations of earlier workshops on research needs in friction but, perhaps, a subset of those that are affected by and important to the dynamic response of a system.

4. SYSTEM DYNAMICS

From the point of view of dynamic systems, the primary roles of friction are loss of power and material wear. Vibration and noise resulting from friction in dynamic systems is another class of problems that often requires detailed knowledge of friction within a system as it is influenced by the dynamics of the system itself. Friction-induced dynamic problems, such as vibrations, noise, and chatter are seen in many industries. In cases where friction is to be minimized, lubricants are used. However, there are many cases, such as webs and clutches, where friction is necessary or lubrication is not feasible. In brakes, for example, friction is necessary to convert kinetic energy into heat without contributing to the vibrational response of the system. Another important function of friction in dynamic systems is as a source of damping, particularly in bolted and riveted connections.

Friction-induced vibration problems may be considered as : (1) those where system response is insensitive to changes in friction and where the resonances or instabilities that result from frictional excitation are inherent system properties; (2) those where system response is determined by changes in friction, such as the case of a change in friction with respect to relative sliding velocity that may lead to instabilities.

Friction forces influence and are influenced by the response of the dynamic systems within which they are generated. In its simplest form, the interaction continuously changes the contact characteristics at the interface. Such changes are superimposed on the 'steady' changes that take place during sliding where vibrations do not occur. Furthermore, oscillations (in 3-D) change the effective normal forces thus changing the friction forces. One consequence of this behavior is that while the mean normal force may be constant, the instantaneous normal force fluctuates. Furthermore, generally normal forces and friction forces both have non-uniform spatial distributions.

Because of the strong coupling between friction force and system response and their time-dependence, predictive models of dynamic friction systems need to be in the form of coupled sets of differential equations. For example, for a simple two degree-of-freedom system which is free to move in the tangential and normal directions, with corresponding displacements x and, respectively, the gross dynamic motion of the body and the time-dependent changes of contact area and temperature are can be expressed as:

$$\begin{gathered} D^{(1)}x=F_t(x,\dot{x},y,\dot{y},A_c,\theta,...) \\ D^{(2)}y=F_n(x,\dot{x},y,\dot{y},A_c,\theta,...) \\ \nabla^{(1)}A_c= f(x,\dot{x},y,\dot{y},\theta,...) \\ \nabla^{(2)}\theta= g(x,\dot{x},y,\dot{y},A_c,...) \\ \vdots \end{gathered}$$

where $D^{(1)}$, $D^{(2)}$ represent differential operators that describe the motion of the system and x and y, and their derivatives, define the relative displacements and velocities of the dynamic pair in the direction of motion and normal to it, respectively. A_c and θ represent the true contact area and temperature, say, of the bulk which depend on many parameters including the dynamic response of the system. The differential operators for the contact area and temperature field are based on the theories of elasticity and heat conduction. F_t and F_n are the tangential (friction) and normal forces, respectively, each a function of system and operational variables. While the equations above show only a select number of physical parameters on which friction depends, a complete set of such equations includes the many other variables that influence friction that also are time-dependent, as implied by the dotted line above. Thus a complete set of equations indicate the interrelationships of the many parameters that influence friction with its dynamic response.

The purpose of this report is to identify and recommend research topics that would lead to the development of friction force expressions that explicitly include their dependence on system dynamics.

5. APPLICATION

Because of the complex relationship between the dynamic system response and the friction force at an interface, any sets of equations (expressions) which describe this relationship are application specific; yet, they arise from a common set of physical phenomena. It is the common set that is emphasized in this report. In order to focus discussions, at the start of the workshop it was decided to consider one application as an example of the interaction of friction and system dynamics: brakes in automobiles and aircraft. This application was also identified at the first workshop as one having a significant economic impact and being intractable. Because brakes operate under a broad range of different sliding conditions, the outcome of the discussions are expected to be applicable to many other dynamic systems.

Brief Description of Brakes

In its simplest form, an automobile brake may be considered as a rotating disk with two pads mounted on either side inside a caliper. When hydraulic pressure is applied, the pads contact the rotating disk and decelerate it by means of friction. Brakes are designed to dissipate kinetic energy into heat. However, some of the kinetic energy goes into vibrations of the brake and caliper (and sometimes the suspension). In the case of aircraft brakes, stacks of annular disks are squeezed together to stop the rotors attached to the wheel.

The observed dynamic responses of brakes range from resonant excitation of any combination of vibration modes to instabilities. Such different vibration responses are associated with different design, operating, and environmental conditions. Lack of repeatability of vibration responses, even under seemingly identical operating conditions, is a common characteristic of brakes and other friction-excited dynamic systems. Observations suggest that dynamic response characteristics of friction-excited systems, such as brakes, are very sensitive to the environment, such as humidity, and to operating parameters such as normal pressure. A small change in normal pressure can lead to a change of the vibration response from one that is harmonic to one that is chaotic.

6. IDENTIFICATION OF FRICTION PHENOMENA

Friction occurs whenever two solid bodies, in relative motion, contact one another; it is a means by which kinetic energy is dissipated. Solid friction is usually described as a force which acts to oppose the motion of an object. Although the friction coefficient (friction coefficient = friction force / normal force) is often approximated to be constant for a given system (Coulomb approximation), it can actually be quite variable, the result of a complex set of phenomena which may differ in relative importance from one system to another. In fact, the friction coefficient for a given system is not usually constant, but can vary with time, sliding velocity, and other operating parameters.

Several processes that contribute to friction have been identified:

Plastic deformation. This involves permanent or irreversible deformation which results from tangential surface traction and/or plowing. Plastic deformation can occur in the near surface regions of the contacting bodies or in third body particles. The mechanisms of energy dissipation in plastic deformation include production and motion of point and line defects, and the excitation of lattice vibrations. In each case, mechanical energy is transformed to internal energy.

Dynamic friction pairs have been studied by tribologists in subjects such as fretting fatigue by which fatigue processes are accelerated by fretting (low amplitude sliding). Plastic deformation leading to ductile fracture is accelerated by low-amplitude vibrations. This effect is called "plastic racheting" and is analogous to fatigue, in that the plastic deformation is driven by low-amplitude cyclic stressing. But, unlike high-cycle fatigue, which takes place in elastically-deformed materials, plastic racheting takes place in materials which are deforming in the plastic regime. Brittle fracture can also be accelerated by low-amplitude vibrations that produce tensile stresses.

Anelastic deformation / Material damping. Although the deformation is not permanent, energy is dissipated by several different means: viscoelastic deformation resulting in internal damping, elastic hysteresis at the micro-contact level, and propagation of elastic waves.

Viscous dissipation. This includes viscous shear of thin liquid lubricant films and the shearing of layers of solid third-body particles (e.g., wear debris or lubricant films). The processes involve displacement of atoms, molecules and/or particles in a time- and rate-dependent manner. Mechanical energy is transformed into internal energy in the form of molecular motion.

Adhesion / Fracture. Mechanical energy is transformed into surface energy whenever new solid surfaces are created by fracture. Fracture processes occur in the production of wear particles, in the fracture of third-body particles, and during the separation of surfaces which have become bonded together through adhesion.

Vibrational excitation. Vibrational excitations take place at contacting asperities, third-body contacts, and during bulk slip or plastic deformation. Atomic or molecular vibrations at these surfaces are converted to lattice vibrations of the bulk or substrate, which ultimately result in an increase in temperature in the contact region. In addition, elastic waves are generated within the bodies that may give rise to time-dependent changes of true contact areas and lead to sound radiation.

Chemical reaction. This includes the formation and destruction of compounds, phase changes of the contacting materials or third bodies, and reactions between the sliding bodies and third-body particles. Some of these reactions may be a byproduct of other frictional energy dissipation mechanisms which raise local temperatures and thus accelerate reaction rates. Other reactions may involve direct energy dissipation or conversion of mechanical kinetic energy into chemical energy.

Photo-emission. This involves the emission of photons from sliding surfaces by the process of triboluminescence. This mechanism does not normally dissipate a significant fraction of frictional energy.

Triboelectric processes. Electric charges can influence friction of insulators and semiconductors; on the other hand, friction can induce electric charge in such materials. The frictional behavior of magnetic materials can also be affected by sliding in a magnetic field.

All of these frictional processes occur in and around the real area of contact between the sliding bodies. They may take place either within the sliding bodies, within the third bodies which separate the two sliding surfaces, or at the interfaces between the bodies. It is through these processes that velocity differences between the bodies are accommodated. In addition, it is through these processes that mechanical energy is transformed into internal energy, which is most often evidenced by an increase in the temperature of the sliding bodies. This increase of temperature, frequently called frictional heating, occurs in the contact region where the frictional interactions take place, and the temperature increase may have, in turn, an important influence on the frictional processes themselves.

In addition to frictional heating, the kinetic energy of the frictional pair is converted into energy of other forms by the frictional processes described above. These other forms of energy include increased surface energy, deformation energy, tribo-chemical energy, tribo-emissions, including sublimation and luminescence, and system-level vibration and sound. The conversion of kinetic energy to those other forms of energy are illustrated in Fig. 1.

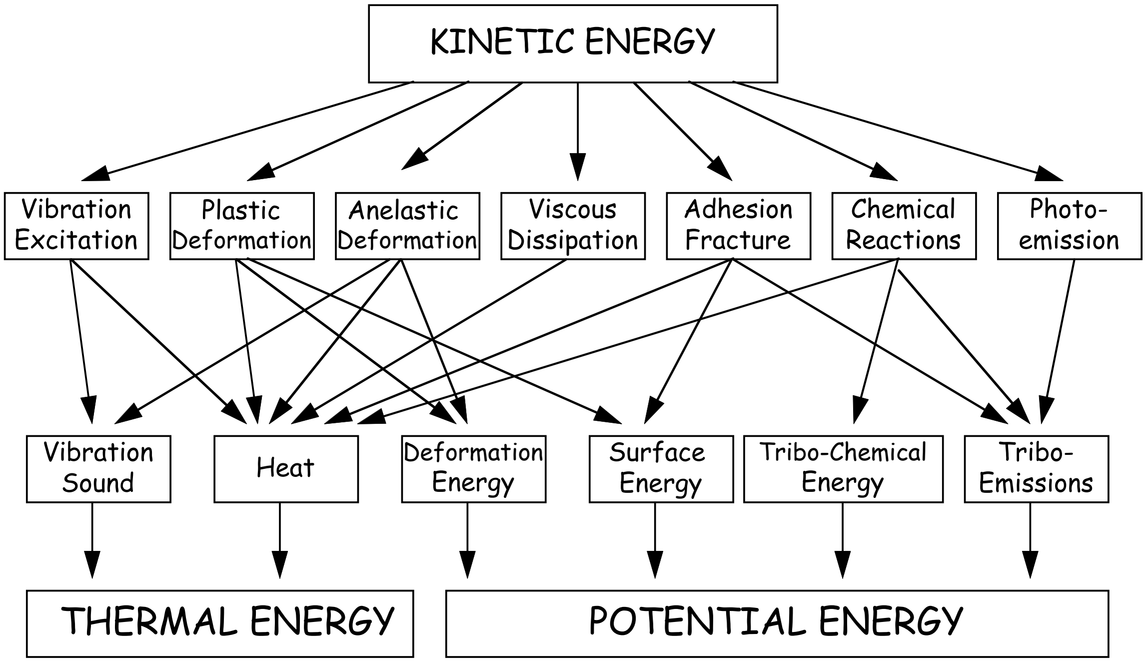

Fig. 1 A schematic description of friction processes and intermediate energy forms.

Some traditional descriptions of sliding friction have grouped frictional interactions into two contributions, an adhesive or surface term and a deformation or volumetric term. The processes listed above could be considered to be a further breakdown of those two terms into more fundamental mechanistic processes. Some of the processes listed above, i.e., plastic deformation, anelastic deformation, and viscous dissipation, act primarily in the bulk volume of the materials, whereas chemical reaction, photoemission, and tribo-electric phenomena are predominantly surface processes. The other two processes, fracture and vibrational excitation can occur either at the surface or in the bulk.

Any model of friction in a given sliding system should consider which of the processes described above may be active in that system, and dynamic models must consider the time- , force-, and velocity-dependence of these processes.

7. MODELING ISSUES

Each of the processes listed in Section 6 may be included in a model of friction for a dynamic sliding system such as a brake. However, the modeling process involves a number of issues, only some of which can be handled easily at this time.

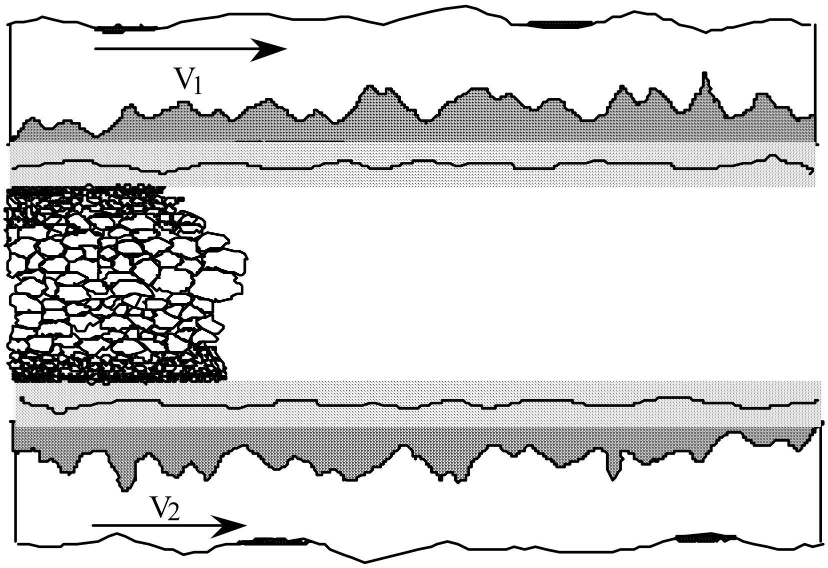

Fig. 2 A schematic depiction of friction interface with third body between sliding surfaces.

Plastic deformation. Numerous models of plastic deformation in sliding contacts have been reported in the literature. The asperity plowing model of Bowden and Tabor [2], relates the deformational component of friction to the slope and size of contacting asperities and the materials. Challen and Oxley [3] used finite element modeling to relate plastic deformation in the region around a contact to surface traction within the contact zone. More recently, Kapoor and Johnson [4] have suggested that the progression of plastic deformation in repeated sliding contacts occurs by cyclic deformation in the plastic, not elastic, regime; they have proposed a “racheting model” to describe wear processes during cyclic plastic deformation. These ideas could be included in a frictional model of a dynamic sliding contact, but there are many issues which must be resolved before such a model could be implemented successfully. Among the unresolved issues are:

- Properties of the contacting materials (including third bodies and mechanically mixed layers; Fig. 2) are not known at the very high plastic strains and strain rates encountered in sliding contacts. These properties would have to be determined over the range of temperatures found in the contact region.

- The real area of contact between sliding bodies and between those bodies and the third-body debris particles is seldom known with any certainty. The distribution of real area and the surface traction within the contact area are also unknown.

Anelastic deformation / Material damping. Models have been created for elastic hysteresis and viscoelastic losses in rolling contacts involving elastomers and viscoelastic materials, but little has been done for sliding contacts. From previous analyses, it appears that these losses may be more important at low deformation rates (low sliding speeds) than at higher rates. The energy which is transformed to heat by means of anelastic deformation processes may be particularly important, because the properties of visco-elastic materials are very much affected by temperature. Any attempt to include these phenomena in a friction model would require that the following issues be addressed:

- The rate-dependent viscoelastic and hysteretic properties of contacting materials are required.

- As is the case for the plastic deformation process, models for the anelastic deformation require knowledge of the real area of contact and traction distribution within the contact.

Viscous dissipation. A considerable amount of work has been done in modeling the behavior of thin liquid lubricant films, and in recent years there have been successful measurements of the properties of such films under conditions of high shear rates and high pressures, where they may display “solid-like” behavior.

- There is more work needed to extend the thin film liquid film models to mixed lubrication conditions.

- There is a need to determine the properties of a wider variety of lubricant films at high shear rates and over a wide temperature range.

Several types of models have been developed to study the rate-dependent dissipative (pseudo-viscous) behavior of solid third-body films. Numerical models study the behavior of the particulate films as a summation of the contributions from each of a large number of particles. Continuum models, on the other hand, consider the behavior of the third-body films and interfaces between those films and the other bodies, in terms of average rheological properties of each layer. Both types of models require information that isn't necessarily known a priori and need further information.

- There is a need to determine properties of individual particles at shear rates and temperatures encountered in actual third body films.

- Knowledge is required about the important interactions between particles due to sliding or normal impacts.

- Data is needed about the average rheological properties of actual third-body films over a range of temperatures and strain rates.

- Information is needed about the interface regions (known as the screens) between the third-body films and the sliding surfaces.

Fracture. The fracture process results in the generation of new surfaces, and the surface energy of those areas accounts for some of the energy dissipated in sliding contact. These surfaces could be created through fracture of asperities, through the initiation and propagation of near-surface cracks which result in wear particle formation, and through the breaking of bonds which have formed between the sliding surfaces. Surface energy of the newly created surfaces is the primary measure of the energy dissipated through this process, but it must be realized that each of these surface generation processes usually involves a very large amount of energy dissipated by other process (e.g., plastic deformation) leading up to the fracture event. If one had complete knowledge of the amount (area) of new surface created by fracture processes and the composition of those surfaces, one could presumably model the energy dissipation through fracture. However, in order for this to happen, there are two steps that must be completed.

- There is a need to be able to predict the rate of new surface generation through each of the fracture processes.

- It is necessary to have a measure of the surface tension (energy) of the newly created surfaces.

This task is made more difficult by the fact that the fracture processes in sliding contacts are imperfectly understood. For example, the questions of how a crack is initiated in the region of a sliding contact and how it propagates when subjected to combined compressive and shear traction have not yet been answered.

Vibrational excitation. Excitations of atomic and molecular vibrations are the basic mechanisms by which bulk kinetic energy is dissipated into internal energy appearing as a temperature increase. During sliding of one surface over another or during plastic deformation of bulk solids, atomic motions are excited. These motions of individual atoms are coupled to the motions of other atoms in the solid and thus localized vibrational energy is transferred to vibrational motions of atoms in the bulk solid and ultimately manifests itself as a rise in bulk temperature. Electron and photon emissions can also be stimulated by transfer of strain energy, but are believed to contribute very little to friction processes except in special materials whose physical properties are highly susceptible to low levels of "radiation" damage.

It is also important to note that in addition to exciting much higher frequency atomic vibrations, sliding motion of solids can excite structural vibration modes or acoustic waves. Structure-borne waves not only alter the contact area distribution but also influence the normal force distribution over the interface. The excitation of elastic waves are associated with the surface geometry (waviness, roughness, asperity distribution) as well as bulk material properties and gross dynamic characteristics of the system.

Molecular dynamic (MD) simulations provide the most detailed picture to date of processes involving excitation of atomic motions. MD simulations of friction are performed by solving Newton's equations of motion for two lattices of atoms with or without surface films in sliding contact under a load. Requiring a high-speed computer to perform millions of calculations for each femtosecond of real time, MD simulations give friction coefficients, strain fields and temperatures of tribocontacts encompassing roughly 10^6 atoms on two surfaces. The reliability of these "computer experiments" depends strongly on the validity of the interatomic and intermolecular potentials used in the calculations. At present, the lack of generalizable potentials limits the use of MD simulations of friction to simple metals, polymers, selected molecular films and one oxide-metal system, Al_2O_3 on Al.

Computational limitations restrict the duration of sliding that can be accurately simulated to approximately a picosecond. To extend the timescale at which friction processes can be modeled computationally, investigators are developing Monte Carlo techniques and finite-element methods to model friction. Employed alone, these techniques cannot duplicate the detailed microscopic views of friction processes available with MD simulations. However, in combination with MD simulations used to establish realistic boundary conditions, Monte Carlo techniques and finite-element continuum models offer the chance to simulate friction processes from atomic timescales (femtoseconds) to measurable time scales (milliseconds).

Approaches to friction modeling using the first principles require continued developments in several areas.

- Continued development of molecular and atomic potentials that yield physically realistic responses is needed.

- There is a need to develop improved algorithms of increasing both the size and the duration of events that can be simulated by MD methods.

- There is a need for the development of coarse grained methods which will allow simulation of important parameters over long time scales without necessarily yielding the wealth and depth of information of molecular dynamics.

Chemical reaction. Chemical reactions can take place during sliding of solid surfaces against one another. These reactions occur in "screens" (surface films) and within third bodies. Normally, products of chemical reactions can be predicted using equilibrium thermochemical data, and many examples of tribochemical products containing expected phases have been published [5]. However, under stresses of tribological contacts, non-equilibrium reaction products can also be generated. Heinicke [6] gives many examples of non-equilibrium products formed during ball milling. Besides forming new compounds, sliding can produce phase changes in compounds. Finally, chemical reactions both produce and destroy defects in the surface. Defects appear in all compounds formed at temperatures above absolute zero to satisfy the second law of thermodynamics. Defects are also generated at interfaces of films on substrates (e.g., Fe oxide on steel) due to lattice mismatches. Defects, however, are the most reactive sites on surfaces, so chemical reactions that form surface films reduce the number of defects and therefore the reactivity of surfaces.

Chemical reactions can influence friction in many ways. They can liberate or absorb heat, thereby changing the temperature. They can produce new compounds and phases, changing the mechanical properties. They can form or destroy bonds at the interfaces, thereby promoting or restraining “adhesive” junctions. Rabinowicz [7] has developed “compatibility” charts to identify material couples that give low and high friction in sliding contact. Reactions in adsorbed films can soften the materials (lowering both modulus and yield strength) in both metallic and nonmetallic solids (Rehbinder effect). Finally, defects produced by chemical reactions can enhance the reactivity of the surface and alter the chemistry of lubricants in contact with the surface.

There are several issues that need to be addressed in order to allow development of models that incorporate the effects of chemical reactions:

- There is a need to know the compositions of interfaces in order to begin formulating the possible reactions that might lead to changes in frictional properties.

- Reaction thermodynamics must be known under the conditions of pressure and temperature that are prevalent at the interface.

- Reaction rate must be understood in order to determine whether or not a reaction will occur to an appreciable extent on the timescale of the sliding event. This requires knowledge of the temperature.

It is still not clear whether strain-induced (non-thermal) reactions are important contributors to interfacial chemistry.

8. RECOMMENDATIONS

Research needs in the area of friction and system dynamics can be grouped as those related to modeling of friction, measurements, and issues related to repeatabilty of friction phenomena in dynamic systems. As such, the research opportunities in this area should also be viewed as having near- and long-term impact on many of the problems industry has been facing -- brake noise and vibration being one such example. While it will take significant resources and time to fulfill many of the research needs, particularly those necessary for comprehensive modeling of friction, their impact will be also significant, albeit in the long term. In the meantime, however, it is recommended to also place emphasize on research, particularly those areas that can yield empirical, but quantitative (as opposed to qualitative) information that can be used in continuum- and engineering-scale models without having to wait for the development and computability of atomic- and molecular-scale models for the same purposes.

Regarding research needs on modeling of friction, a set of recommendations were made in the report resulting from a previous workshop [8]. These were broadly based and covered most aspects of friction and lubrication; both technological needs as well as basic research needs were identified. The emphasis of the current workshop is on the effects of system dynamics on each of the parameters affecting friction. As such, it is recommended that investigations of parameters contributing to friction consider the effects of system dynamics, for dynamic response of a friction pair causes time-dependent changes at the interface and the bulk of the friction pair during and following their relative sliding motion. The parameters that have time-dependence include true contact area and its distribution, material properties of the surface and subsurface, temperature distribution within the same and the like. Furthermore, these changes may have different time constants.

Friction Modeling

The modeling issues listed in Sec. 7 serve as a clear framework for defining the types of research that are needed to make progress in the understanding of the interaction of friction and system dynamics.

Interaction of Friction-System Dynamics

- There is a need to develop friction models that represent the interactive nature of friction and system dynamics. Such models also need to integrate results of research on microscale friction.

- There is a need to develop a better understanding of the time-dependent nature of the interaction among key friction parameters and how they are affected by the dynamics of the system.

- There is a need to develop methods to measure the adhesive component of friction at the mesoscopic and engineering scales as inputs in the development of engineering-scale models.

- There is a need to develop criteria to ascertain the influence of system dynamics on friction phenomena including their measurements.

Measurement Needs

In many respects, progress in tribology is limited by the ability to make consistent measurements more than the ability to provide models of the phenomena that are deemed to be important. Many of the problems associated with the understanding of friction during "steady-state" sliding continue to plague our understanding of this broader problem. Lack of repeatability of friction experiments at the engineering scale is well known.

  - It is recommended that the issue of repeatability is addressed in future research.

  - Reproducibility is needed between laboratories and between different systems used for friction measurements.

  - A single system_or a few model systems need to be identified to serve as the focus of research in order to identify benchmark measurements which can be reproduced among all laboratories investigating tribological phenomena.

  - Measurement systems need to be identified which truly isolate the relative contributions to friction of the phenomena list in Sec. 7.

- There are acute needs for experimentally obtained friction information that are otherwise not available through modeling. As such, there is a need for new sensors for sliding interfaces, and a need for the development of techniques to "de-convolve" the effects of system dynamics in measurements of friction phenomena. There is also a need to develop sensors to measure friction at the interface.

- There is a need to characterize and measure the time-dependent nature of surface topography, particularly at mesoscopic and continuum scales, where roughness and waviness of surfaces strongly influence friction through changes in true contact areas.

The need to further understand the role of dynamics in friction complicates the measurement process. System dynamics undoubtedly influence friction in real world applications and probably influence the results of laboratory measurements, even under conditions in which they are ignored. The major variable which must be included in studies of friction is time dependence. As avenues for initial experimental investigation of the effects of system dynamics on friction we make two suggestions.

- Systems must be designed for the study of friction under conditions of time varying load.
- Systems must be designed for the study of friction under conditions of time varying sliding speeds.

There is a need to measure the dynamic aspects of friction properties such as surface roughness and deformation, chemical composition, and heat generation and temperature distribution. The need is acute for repeatability of such measurements.

Finally, it is recommended that a series of focused conferences be held on aspects of friction research that address the recommended research topics in this report.

Technology needs in this area were outlined in the report of the previous workshop [1].
The recommendations of the current workshop are focused on the influence of dynamics on friction modeling.

9. ACKNOWLEDGMENT

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