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The State of Modeling in Friction and Wear and a Proposal for Improving That State

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Abstract—Over 300 equations and models were found in the leterature on friction and wear. No single equation on limited group of equations could be found for general on practical use. Recommandations are offered for improving the future yield of useful equatio

I. Introduction

An engineering design one very difficult step is predicting friction in, and wear life of mechanical products. This applies to all states of sliding, ranging from dry sliding to boundary lubricated sliding. Product designers must therefore respect to using empirical or semi-empirical metals in which the design process is "shell-based".

Broadly, there are three interacting reasons for the paucity of models. The pivotal reasons is that friction and wear are the result of very complicated processes, and strongly influenced by many sliding conditions. The list exceeds 100 when all types of wear are considered by selected mature authors.

The great number of variables include several from each of several academic disciplines. These include chemistry and chemical engineering, material science and engineering, mechanical engineering and system modeling, fluid and solid mechanics, and some branches of physics. Each of these disciplines uses a difficult "language" from the others, each uses different methods in research, each uses different hardware and instruments, and these often publish in separate journals. It is therefore not suprising that so few problems in friction and wear have been completely characterized.

It is clear from the lustory of technology that progress is marked by the extent to which the systems under study have been modeled, that is, where equations have been developed to ink the relevant parameters and variables to describe how a system functions. The topics in friction and wear are not well developed: a progress report follows.

2. Friction Modeling

There has been virtually no progress in modeling friction since the very elementary mechanics approach of the 1930's. The equation for coefficient of friction $\mu = F/W$, where 'F' is the force to slide and 'W' is applied load; and Tabor [1] suggested that $F = As$, where 'A' is the summation of all of the microscopic contact areas and 's' is the shear strength of the bond in those areas. The logical development of this idea leads to the conclusion that μ should always be somewhere in the range, 0.16. to 0.2 depending on what assumptions are preferred for the relationship between hardness and shear stength (of metal in Tabor's work). In recognition of the wide range of coefficitent of friction in practice, Tabor developed another equation,

$$\mu = \frac{1}{\alpha * \sqrt{k^{-2} - 1}}$$

where α is 3, taken from an approximation of a plastic "yield criterion". The quantity 'k' is the ratio of the shear strength of an unspecified residue or substance on surfaces, to the shear strength of the substrate under the residue. This equation, though simple and largely dismissed as irrelevant in the last 40+ years, is probably the best available. It is based on the recognition that no practical surface is neat and pristine as is virtually always assumed in mechanics. All solid objects, however carefully made and handled, contain within (or upon) their surface some product of chemical conversion, or condensed matter from the environment. Metal (except gold) are covered with oxides, many ceramic materials are covered with some hydrated from of the substrate, and polymers are often covered with bloomed plasticizer. All are covered with condensed water vapor and probablly also with condensed hydrocarbons.

Indeed, many other equations and models for friction are offered in the literature, some based.on the assumption of the need for two terms or even for three terms. Some reflect the fact that sliding surfaces may contain embeded hard (carbide) particles, which from grooves in the opposing surface upon sliding. Some are based on models of atomic bonding and separation, including consideration of non-conservative little vibration However, none has come to light that incorporates what is known about real surface, sliding in real environment. Very likely, the authors of the simple models expert that someday in the future their medels can be expanded to inclund newly found properties of materials.

3. Wear Modeling

There are no generally useful wear equation abailable. Indeed, many equations have been published and some are quite useful, but they require considerable knowledge of wear on the part of the user to implement. None stands by itself as do equations for beaming bending, or for the calculation of the natural frequency of simple dynamic systems. By comparison with other fields, we can readily understand why wear has been so difficult to characterize, and that is becaus of its great complexity.

The complexity of existing wear equations was shown in an analysis done by Meng [2]. He found over 300 equations for friction and wear in a search through 546 papers published in the years 1957-1992. Of these, 182 equations were wear equations. The most striking aspect of these equations is the great number of variables cited, well over 100. New variables appeared each year from 1957 to 1992, indicating little convergence of thought on formulating wear equations over that time. Another interesting observation is that few authors agree on whether any particular variable belongs in the numerator or denominator of an equation, except the variable 't' for time.

Meng attempted to detrmine which equations were the most authoritative by tracing the thoughts and ideas inherent in each, and by counting the citations of a particular author by other authors. He focused on the equations for erosion by solid particles, and found 28 that appeared to encompass most of the historical knowledge on the subject. These equations contained a total of 33 variables beside the constants "of proportionality" and the seemingly inevitable other constants that arise whenever equatins are witten. The distribution of these variables and constants in the cited 28 equtionss is shown in Table 1. From this distribution we note that authors form different disciplines almost exclusively cite variables from their own discipline, some from elasticity, some from thermodynamics and some from material science, etc. Few authors cited more than 4 or 5 variables, and thus it is not possible at this time to "stitch togeter" one universal equation from these 28. Perhaps the most revealing indication of incompatibility among these equations is seen in the exponents 'n'on the velocity term 'V': these range from about 2 to 6. Ordinarily one would expect that erosion damage would be related to the momentum transfer from the eroding particle to the target, so 'n' should be near 2

Table 1. Steps in developing wear models, for metals in a practical unlubricated environment

1		2		3		4
Develop a statement of the sequence of material mixing at the sliding interface, involving base material, products of chemical conversion, and adsorbed substances.	→	Develop a picture of planes and zones of weakness that develop in the mixed interface material.	→	Develop a picture of the distribution of the size and shapes of loosened particles that form from the mixed interface material.	→	Develop an estimate of the fraction of paricles that recirculated in the contact region and the fraction that departs as wear debris.

[include a theoretical estimate of the resistance to sliding (friction)] depending on the efficiency of that transfer. However, the large range of cited values of 'n' probably indicates other problems. In some instances there may by melting on the target surface which is a phenomenon that is not readily repesented by the variables from contact mechanics, or perhaps the cited properties of hardness and fracture toughness in some equations should by dynamic values rather than quasi-static values. Without a major study these possibilities remain only possibilities, but the nature of the problem of writing wear equations in general seems apparent: there are more variables controlling the wear rate of materials than any study encompasses, and effective coordination among investigators has not yet occurred (and likely cannot occur given the nature of research funding).

Of the 182 equations, 154 described 'other' modes or types of wear. These equations are even less likely that the 28 erosion equations to constitute the ; 'pool' from which one or two universal equations could be constructed. The most obvious difficulty is the great diversity in identifying the type, mode, mechanism or process of wear under study. Few of them, such as adhesive wear, abrasive wear, slidig wear, etc. define very specific or unique material removal events or unique material removal events or sequences. Further, several frequently cited material properties, such as hardness or Young's modulus do not relate to material loss at all, and few other cited material properties resist the assumed mechanisms of material loss.

4. Modeling Bounday Lubricantion

Boundary lubrication appears to be defined in two ways, one emphasizing the mechanics of contact and the other a chemical sequence. The mechanical approach may be explained by comparing 'h' with a surface roughness parameter, 'σ' of the contacting pair, often expressed as λ (=h/σ). If λ>3 the sliding surfaces are considered to be adequately separated by a fluid film.

If λ>3 the highest asperities will "collide". With still smaller values of λ more contact occurs, which finally produces a form of surface damage known as scuffing. Scuffing is usually sudden, and usually is manifested as a servere roughening of the surface with little loss of material. Scuffing may be prevented, or the equivalent - the load carrying capacity of surfaces may be increased by the formation of protective films on surfaces by chemical action between a lubricant and the sliding solids. The sliding "boundary" is coated with a "lubricant" and this is the sense of Hardy's [3] definition of "boundary lubrication".

The frictional and wearing properties of boundary lubricated systems are rarely modeled, simply because the underlying phenomena are only partially understood, and then narrowly in the terms of specific disciplines. The several "scuffing criteria" of models that have been published in the last 50 years are inapplicable because they incorporate only half of the phenomena that are know to be operative in boundary lubication. Protective boundary films require both the proper combination of mechanical conditions (load, surface speed, lubricant viscosity, etc) and the proper chemical conditions simultaneously.

There has, however, been some progress in understanding some of the variables that control or influence boundary lubrication. A list of variables is given below but it does not even provide the skeleton of a model for scuffing resistance or load carrying capacity of lubricated surfaces. This is an unconventionally use to define the perblem of boudary lubrication. Note that the proformance of boundary films may be influenced by the presence of debris derived from mechanical removal of substrate material.

Each of the topics in the list has been studied to some extent and references to journal articles on the topics are given in the Reference list below. The titles of the papers are given so that the reader may discern the sense of what is known about each topic. The work is clearly incomplete. Very man authors beside those in the Reference list have contributed thoughts but usually not within an organized context. Most of these authors are referenced in the papers cited below.

4-1. Boundary film effects:

a. Generation rate (determines break-in potential), dependent on: [4,5,6]
   1. Sliding energy (PV)
   2. Roughness, initial and dynamic [7]
   3. Chemical availability (including thickness of film vs. the lateral extent of contact regions)

b. Equilibrium thickness and mechanical properties of boundary films(determine friction):

dependent on: [8,9]
1. Severity of sliding contact
2. chemical preactions.

4-2. Effects due to boundary film material and debris from the solid surface.

a. Chump accumulation conditions (determines probability of local starvation and scuff initiation) [10,11]
   1. Repeat pass · · · · · reciprocating
   2. Exact tracking · · random tracking · · no tracking
   3. Low compliance · · · · · high compliance
   4. Steady sliding · · · · · severe vibration

b. Loss rate versus retention rate (determines wear rate)
   1. Tendency for loose debris to be compacted into a "transfer film" [12]
   2. Tendency for substrate material to fail to from debris [13]
   3. Chemical conversion rate versus film loss rate
   4. Solubility in or flushing by fluid

5. Recommendations

It is clear that wear equations cannot be synthesized from the many existing equations, and it is equally unlikely that many applicable equations will emerge using the approach of the past. Equations will continue to appear, however, and doubtless ome that seem to be totally impractical at this time may evetually be the basis for future useful equations.

Wear modeling and equation writing will benefit from a new approach and the following suggestions are offered:

a. Abandon efferts to model wear in terms of the current list of wear mechanisms (eg., adhesive, abrasive, erosive, fatigue, etc). See Table 2. These terms only serve to diverge thinking on real wear processes. It is not surprising that the long-standing wear mechanisms are still in use: there are few alternatives.

b. Develop full descriptions of the evolution of material changes of sliding surfaces, including a description of the formation and movement of fragmented particles in the interface region. Collaboration with researchers in materials studies is vital in this effort.

An example is given in Table 3 for sliding of metal. Most definitely, when a body of material A slides on a body B, the two original substrate materials do not slide against each other, even at the start of sliding.

A slightly different list is required for lubrication sliding, for ceramic materials, for polymers, for composite materials, etc.

c. since friction forces add to the stresses and temperatures imposed upon all substrances in the interface, friction should be represented in some way that is more fundamental and locally distributed than in the from of a coefficient of friction. The latter is a useful term for mechanical design purposes, not for research in wear.

d. Adjust editorial polbices of journals to consider substantive exchange of information on friction and wear in the experimental and pre-modeling stage. This includes pulishing un-interpreted data from experiments. And, journals usually avoid such papers because they take up space, and because of the seeming unscholarly nature of bare data sets. However, wick proper guidebies "data" papers could adance the cause of modeling more surely than will our publishing practices. Suidlines would include:

(1) The equipment(shape, dynamics, instruments, *et al*), materials, enviroment and method of running the test must be so well described that a reacher at some other location than that of the author could duplicate the experiments and obtain statistically similar results.

(2) All data should be listed with an assessment reliability and reproducibility,

(3) Very wide ranges of several variables should be included

(4) Transients over time and location on the specimen should be reported in some useful manner, and not concealed within "time average" values.

(5) Micrographs, roughness traces and supporting information should be obtained to "follow" changes that occur during tests.

(6) Amature judgement on the foults of the work and suggestions on how progress on modeling can be made. It would also be helpful if author could indicate their focus in tribology since this guides their research scope and methods.

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