WEAR – MATERIALS, MECHANISMS AND PRACTICE

Edited by

Gwidon W. Stachowiak

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WEAR – MATERIALS, MECHANISMS AND PRACTICE

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Series Editors' Foreword

Tribology is concerned with understanding the behaviour and performance of the components of machines and equipment, with surfaces that are subject to relative motion, either from other components or from loose materials. It therefore has a wide range of applications across many industries, and also in medicine in understanding the mechanism of operation of the joints between bones. The *Tribology in Practice Series* of books aims to make an understanding of tribology readily accessible and relevant to industry, so that it can be brought to bear on engineering problems.

This latest book in the series, *Wear – Mechanisms, Materials and Practice*, edited by Gwidon Stachowiak provides a comprehensive review of the current understanding of the wear of all kinds of materials, and how it can be controlled and reduced. The authors of the individual sections of the book are world experts in the various subject areas. They are therefore able to summarize the currently available knowledge and the ways in which it can be used to solve practical problems. The book will therefore provide a valuable reference work for engineers in industry, as well as being useful for research workers in the field by providing a summary of previous work.

As a Series, the *Tribology in Practice Series* is particularly concerned with design, failure investigation, and the application of tribological understanding to the products of various industries and to medicine. The scope of the series is as wide as the subject and applications of tribology. Wherever there is wear, rubbing, friction, or the need for lubrication, then there is scope for the introduction of practical, interpretative material. The Series Editors and the publishers would welcome suggestions and proposals for future titles in the Series.

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Preface

Wear is the process occurring at the interfaces between interacting bodies and is usually hidden from investigators by the wearing components. However, this obstacle has been gradually overcome by scientists, revealing an intricate world of various wear modes and mechanisms. Since the early wear experiments our knowledge about wear has increased considerably and a significant progress in the description of wear mechanisms has been made. Over the past decades our views and understanding of wear have changed, including the classification of wear mechanisms. Concepts such as abrasion, adhesion and fatigue, originally used in the classification of wear mechanisms, are, now, insufficient. New materials and surface coatings wear in a specific manner. Complex reactions and transitions often take place on the wearing surfaces and our understanding of wear mechanisms occurring is critical to the effective utilization of these materials. Furthermore, if we understand how a material resists wear and friction, then it should be much easier to improve that material.

It is now clear that all known forms of friction and wear are controlled by thin films of material present between the interacting surfaces. It has been recognized since ancient times that supplying liquid or grease to a contact offers a lower friction and wear. If such a film is merely generated by wear of the bodies sliding in dry contact, the wear and friction are usually much higher. In general terms, this film formation controls wear to a large extent and is usually beneficial since it lowers friction and wear. However, there are also instances when film formation raises wear and friction.

In May 2000 Chris Taylor, the editor of the Journal of Engineering Tribology, had asked me to guest-edit a special issue of the *Journal of Engineering Tribology* on the topic of 'Wear/Lubricated Wear'. I found this to be a very good idea and agreed. The special issue was published almost two years later in 2002. The issue contained nine excellent papers covering a broad range of topics representing our state of knowledge on recent developments in the area of wear/lubricated wear. World-leading researchers in the area of wear and wear control, such as Koji Kato, Sanjay Biswas, Stephen Hsu, Ronald Munro, Ming Shen, Richard Gates, Andrew Gellman, Nic Spencer, Said Jahanmir, Ali Erdemir, Christophe Donnet, Brian Briscoe, Sujeet Sinha, Klaus Friedrich, Zhong Zhang, Patrick Klein and Gwidon Stachowiak, contributed papers on various topics to this issue. On completion of this work it became apparent that many researchers and engineers throughout the world would benefit from an expanded version in a book form. So I had presented the idea of publishing this special issue in a more expanded form to the Professional Engineering Publishers Ltd. The publisher was very supportive of the idea. In addition, the Editorial Board of the PEP book series made many valuable suggestions regarding the book content. As a result several additional experts, such as Ian Hutchings, Anne Neville, Ardian Morina, Kenneth Holmberg, Alan Matthews, Yves Berthier, Philippe Kapsa, Siegfried Fouvry, Leo Vincent and Brian Roylance, were invited to contribute chapters in specific areas of wear and wear control. Altogether, six additional chapters were invited and, as a result, a unique piece of work has emerged.

The resulting book represents the current state of art in the area of wear, wear mechanisms and materials. The chapters discuss the latest concepts in wear mechanism classification, wear of metals, wear of polymer and polymer composites, fretting wear, wear mapping of materials, friction and wear of diamond and diamond-like carbon films, wear of ceramics, concept of a third body in wear and friction problems and the tribology of engineered surfaces. Wear in boundary lubrication, effects of lubricant chemistry on wear, effects of surface chemistry in tribology, characterization and classification of particles and surfaces, and machine failure and its avoidance are also discussed. The strength of this book is in its current knowledge of topic and its frequent references to engineering practice. However, this book is not limited to presenting what is already known about wear. It also attempts to present the myriad of new emerging problems and the possible ways of solving them. It shows us that, although we already know a lot about wear, there are still some aspects of it to be yet uncovered and thoroughly investigated. It shows us that new ways and approaches to wear control are still being discovered and implemented in practice. The book also demonstrates what type of new problems we are most likely to be dealing with in the future.

I am very grateful to the authors for sharing with us their knowledge and for their hard work. In particular, I appreciate the time they dedicated to the meticulous preparation of their manuscripts. After all, it is not easy to put an extra task on top of the many other duties and commitments one already has. I am sure this book will provide a valuable reference for people with interest in wear and wear control.

Gwidon Stachowiak

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The Challenge of Wear

I.M. Hutchings

Abstract

While accurate predictive models for wear rate are still an elusive goal, it is clear that significant recent progress has been made in our understanding of many aspects of wear mechanisms and that advances in materials, surface engineering and lubricants, as well as in design methods and condition monitoring, have led to major improvements in the efficiency, lifetime cost and performance of many engineering systems. There is still much potential for future development, and challenges in tribology, especially in the vital field of wear, remain.

1.1 Introduction

To understand the degradation processes known as wear, to predict the rate of wear and to reduce it still form some of the most problematic challenges facing the engineer. The understanding of wear often involves a detailed knowledge of mechanics, physics, chemistry and material science, while its quantitative prediction, even to within an order of magnitude, remains in many cases a distant goal. Although wear can often be reduced by lubrication, the extent of that reduction can almost never be predicted accurately. The following chapters focus on particular aspects of wear and review the current state of our knowledge on this vitally important topic.

1.2 Definitions and Development of Wear Studies

The widest definition of wear, which has been recognized for at least 50 years, includes the loss of material from a surface, transfer of material from one surface to another or movement of material within a single surface [1]. Although a narrower definition of wear has been proposed as ‘progressive loss of substance from the operating surface of a body occurring as a result of relative motion at the surface’ [2], the wide range of engineering applications of concern to

Wear – Materials, Mechanisms and Practice I.M. Hutchings

the tribologist is served better by a broader definition. A simple and useful statement is that wear is 'damage to a solid surface, generally involving progressive loss of material, due to relative motion between that surface and a contacting substance or substances' [3]. This includes (1) degradation by the displacement of material within the surface (leading to changes in surface topography without loss of material), as well as the more usual case of material removal; (2) the wear processes common in machines in which one surface slides or rolls against another, either with or without the presence of a deliberately applied lubricant; and (3) the more specialized types of wear which occur when the surface is abraded by hard particles moving across it, or is eroded by solid particles or liquid drops striking it or by the collapse of cavitation bubbles in a liquid. This definition, quite deliberately, tells us nothing about the mechanisms by which the degradation takes place. These may be purely mechanical, for example involving plastic deformation or brittle fracture, or they may involve significant chemical aspects, for example oxidation of a metal or hydration of a ceramic; in many practical cases, both chemical and mechanical processes play a role [4].

The study of tribology has a long history, extending for several centuries before the word itself was coined in 1965. Early studies of friction were performed by Leonardo da Vinci in the late sixteenth century, and the first quantitative understanding of fluid film lubrication originated with Beauchamp Tower in the late nineteenth century. Wear has entered the scientific arena rather more recently. The design and construction of early machines involved large clearances and rather slow speeds of operation, with the result that, provided gross adhesion or excessive friction could be avoided, changes in dimensions of sliding parts due to wear could often be tolerated with little adverse effect on performance. It was the development of the high-speed internal combustion engine in the early part of the twentieth century that provided the initial driving force for the study of wear which has grown in importance to the present day. Our understanding of wear mechanisms has developed most rapidly with the widespread use of electron microscopy and instrumental methods of microanalysis over the past 30 years. There are now many examples of advanced engineering products, some involving high-speed sliding or rolling and others small dimensions or hostile environments, whose development and successful use are possible only through the understanding and successful limitation of wear processes. These include gas turbine engines, artificial human joints, automotive engines and transmissions, tyres and brakes, hard disk drives for data storage and an increasing number of electromechanical devices for domestic and industrial use. Wear is, however, not always to be avoided: there are many manufacturing processes involving abrasive processing, for example, in which wear is used productively to form and shape surfaces [5].

1.3 Scope and Challenges

In some applications such as bearings, wear (and friction) is of primary concern, while for others the tribological performance of the system, although important, is not the main driver for its design. Thus, in modern engineering, we find increasing use of materials with more attractive combinations of density and mechanical properties than steel, or with benefits in cost, performance or formability, such as polymers, ceramics and various composite materials [6–8]. We also see a rapid increase in the use of surface engineering to provide a cost-effective combination of near-surface performance with desirable bulk properties in engineering components [9, 10]. These developments all pose particular challenges for the tribologist.

The origins of these challenges are many. The conditions to which a surface is exposed during wear are quite different from those involved in the measurement of conventional mechanical properties such as tensile strength, indentation hardness or fracture toughness. The dimensions of oxide or lubricant films, of surface height variation or of wear debris typically lie in the range from 10 nm to 10 μm [9]. In the absence of a thick lubricant film, surfaces make contact with each other at local high spots (asperities) which interact and induce high stresses (up to the yield point in some cases) over distances of the order of micrometres on a timescale of the order of microseconds. For typical speeds of relative motion, the strain rates at these microscopic sites of mechanical interaction can therefore be of the order of 10^4–$10^7\,\mathrm{s}^{-1}$. Not only are the timescales very short and strain rates high, but all the energy of frictional work is dissipated through the interactions of these contacts, often leading to high but transient local temperatures [11]. Even in a lubricated contact, the power density can be remarkably high: it has been estimated that in a thin elastohydrodynamic (EHL) oil film, the rate of viscous energy dissipation is of the order of $100\ \mathrm{TW\,m^{-3}}$, equivalent to dissipating the entire electrical power output of USA in a volume of 5 l.

The difficulties involved in fully describing, and then in formulating models for, the behaviour of a wearing surface are not just associated with the extreme local conditions. The problem is much more complex than that, for at least three more reasons. First, the process of wear itself changes the composition and properties of the surface and near-surface regions; the material which separates two sliding surfaces can be treated as a distinct ‘third-body’ with its own evolutionary history and properties and these properties will often change during the lifetime of the system [12]. Second, the removal or displacement of material during wear leads to changes in surface topography. Third, the mechanisms by which wear occurs are often complex and can involve a mixture of mechanical and chemical processes: for example, in the unlubricated sliding of two steel surfaces, material may be removed by mechanical means after oxidation, while under conditions of boundary lubrication the source of wear is often the mechanical removal of the products of chemical reaction between the steel surface and the lubricant additives [13, 14]. Neither the mechanical nor the chemical interactions involved in sliding wear can yet be modelled accurately. The problem of fretting wear, in which contacting surfaces are exposed to small cyclic relative displacements, has some similarities to, but also many differences from, that of continuous sliding [15].

The case of abrasive wear is in principle slightly more tractable since chemical effects usually play a negligible role, but even here it would be necessary to model the deformation of the material to very large plastic strains, to incorporate realistic failure criteria (to account for ductile rupture or brittle fracture), to allow for changes in surface topography during wear, to account for the inhomogeneity of the material (associated with its microstructure, as it is initially and as it becomes modified during wear) at the length scale relevant to the unit interaction with an abrasive particle and to sum the individual effects of the interactions with perhaps many billions of abrasive particles.[1] The properties of the abrasive particles themselves would also have to be incorporated into a full model: these will include their bulk mechanical properties such as stiffness and strength, as well as a full description of their shape. The difficulties involved in describing the relevant aspects of particle shape alone have stimulated much research [16].

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[1] One gram of abrasive particles 10 μm in diameter represents about 10^9 particles.

In view of the highly complex nature of wear processes and the difficulty of producing realistic models for them, it is not surprising that many discussions of sliding wear start with the simplest possible assumption of the relationship between wear rate and normal load:

$$Q = \frac{KW}{H} \tag{1}$$

where Q is the volume removed from the surface per unit sliding distance, W is the normal load applied to the surface by its counterbody and H is the indentation hardness of the wearing surface. K is a dimensionless quantity which is usually called the *wear coefficient* and which provides a valuable means of comparing the severity of different wear processes. If K, W and H remain constant during wear, then it is implicit in equation (1) that the volume of material lost from the surface is directly proportional to the relative sliding distance, or at constant sliding speed, to time. Equation (1) is usually called the *Archard wear equation*. Archard was perhaps the first to derive the relationship from a plausible physical model in 1953 [17], although Archard himself acknowledged the earlier work of Holm in 1946, and the empirical statement that wear is directly proportional to sliding distance and inversely proportional to normal load was made as early as 1927 by Preston in a study of the polishing of plate glass [18]. An equation identical to equation (1) was also stated by Taylor in 1948 without any indication that it was not already well known [19].[2]

For engineering applications, and especially for the wear of materials whose hardness cannot readily be defined (such as elastomers), the wear rate is commonly stated as $k = K/H = Q/W$. k is often called the *specific wear rate* and quoted in units of $\mathrm{mm}^3\ \mathrm{N}^{-1}\ \mathrm{m}^{-1}$. For a material with a hardness H of 1 GPa (a soft steel, or a hard aluminium alloy, for example), the numerical value of k expressed in $\mathrm{mm}^3\ \mathrm{N}^{-1}\ \mathrm{m}^{-1}$ is exactly the same as the value of K.

Figure 1.1 shows, very approximately, the range of values of K seen in various types of wear. Under unlubricated sliding conditions (so-called dry sliding), K can be as high as 10^{-2}, although it can also be as low as 10^{-6}. Often two distinct regimes of wear are distinguished, termed ‘severe’ and ‘mild’. Not only do these correspond to quite different wear rates (with K often above and below 10^{-4}, respectively), but they also involve significantly different mechanisms of material loss. In metals, ‘severe’ sliding wear is associated with relatively large particles of metallic debris, while in ‘mild’ wear the debris is finer and formed of oxide particles [13]. In the case of ceramics, the ‘severe’ wear regime is associated with brittle fracture, whereas ‘mild’ wear results from the removal of reacted (often hydrated) surface material.

When hard particles are present and the wear process involves abrasion (by sliding or rolling particles) or erosion (by the impact of particles), then the highest values of K occur;[3] the relatively high efficiency by which material is removed by abrasive or erosive wear explains why these processes can also be usefully employed in manufacturing [5].

The values of K which occur for unlubricated sliding, or for wear by hard particles, are generally intolerably high for practical engineering applications, and in most tribological designs lubrication is used to reduce the wear rate; the effect of lubrication in reducing wear

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[2] Although the relevant paper was published in 1950, it had been presented at a conference in 1948.

[3] Equation (1) can be applied to abrasive wear as well as to sliding wear; an analogous equation can also be derived for erosion by solid particle impact, from which a value of K can be derived [20].

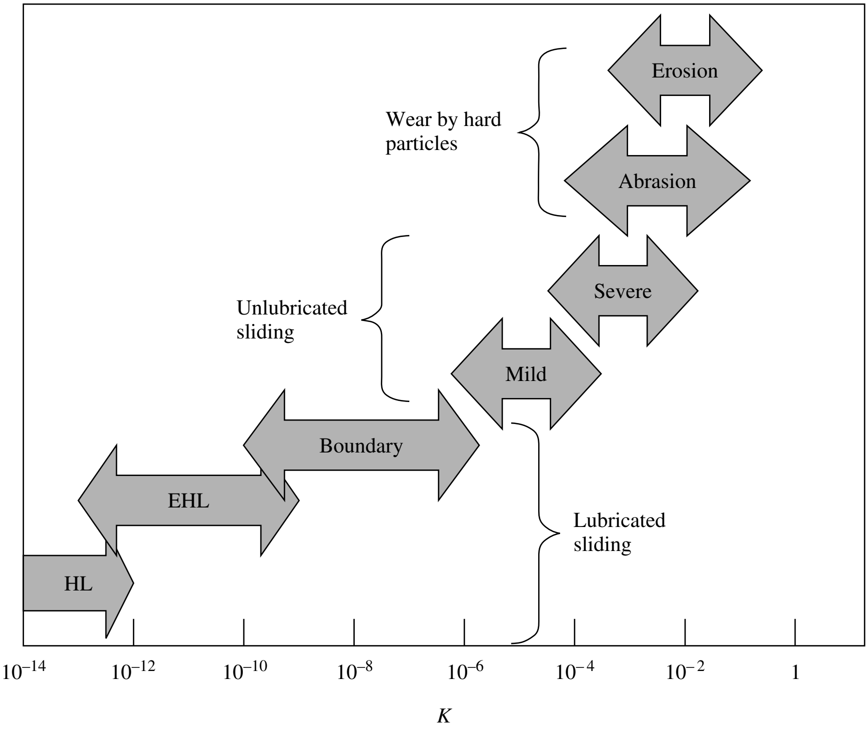

Figure 1.1 Schematic representation of the range of wear coefficient *K* exhibited under different conditions of wear. HL = hydrodynamic lubrication; EHL = elastohydrodynamic lubrication

is far more potent than its effect on friction, and the increase in life which results from the reduction in wear is generally much more important than the increase in efficiency from the lower frictional losses. As Figure 1.1 shows, even the least effective lubrication can reduce the wear rate by several orders of magnitude, and as the thickness of the lubricant film is increased in the progression from boundary to EHL and then to hydrodynamic lubrication, so the value of K falls rapidly. In the hydrodynamically lubricated components of a modern automotive engine, values of K as low as 10^{-19} are achieved [21].

There is a great deal of current interest in improving lubricants so as to achieve low wear rates with thinner films (associated with higher contact pressures). A good protective lubricant film requires the right combination of adhesion to the substrate, film formation and replenishment rate and shear strength [14]; allied with this is the need to find replacements for highly effective additives such as ZDDP (zinc dialkyl dithiophosphate) which contain elements which are detrimental both to the environment and to the long-term operation of automotive exhaust catalysts. Boron compounds are receiving much attention in this context, and there are also attractions in lubricants which can be transported to the sliding surfaces in the vapour phase, especially for very small-scale devices (e.g. MEMS) and for systems operating at high temperatures [14, 21, 22]. There is also active research into lubricants and lubricant additives which are effective for non-ferrous metals, ceramics and engineered surfaces [21].

As our understanding of wear processes deepens, it becomes increasingly important to be able to transfer that knowledge to engineers involved in both the design and operation of machines. Maps or wear regime diagrams provide powerful tools for the design process [4, 7, 23], while increasingly sophisticated methods have been developed to assess and monitor the tribological health of operating machinery and determine the appropriate levels of maintenance [24].

1.4 Conclusions

While accurate predictive models for wear rate are still an elusive goal, it is clear that significant recent progress has been made in our understanding of many aspects of wear mechanisms and that advances in materials, surface engineering and lubricants, as well as in design methods and condition monitoring, have led to major improvements in the efficiency, lifetime cost and performance of many engineering systems. There is still much potential for future development, and challenges in tribology, especially in the vital field of wear, remain.

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