TRIBOLOGY: THE SCIENCE OF COMBATTING WEAR

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Editorial: STLE was very fortunate in obtaining permission from Dr Sheldon R Simon, Manager of B-TIP (Battelle Technical Inputs to Planning) of Battelle, in Columbus, Ohio, to republish their report No. 26 entitled “Tribology: The Science of Combating
Wear”. This 56-page report was copyrighted in 1981 but is now out of print. The contents are applicable today. The report presents the basics of lubrication, friction and wear, in a very readable form with excellent sketches, photographs, tables, graphs and information for practical use. The authors are William A Glaeser, Richard C Erickson, Jerrold W Kannel, and Keith F Dufrane. Their biographies are presented in this issue. Mr Erickson is no longer at Battelle. These authors are from the Tribology section of Battelle, which continues to be one of the nation’s best Tribology research centers. Battelle contributes significantly to the solution of lubrications and wear problems in industry.

The Editorial Committee has divided the report into ten sections, and will publish them in the “Back to Basics” section of Lubrication Engineering. The whole report may be offered later as an STLE Special Publications. The Introduction is presented as Part I in this issue.

We can all be grateful to Battelle for sharing this valuable report with the members of STLE. Mr Simon wrote, “because of the educational nature of your endeavour, we are happy to co-operate.” The writing is a valuable contribution to the Society’s obligation to disseminate Tribological information. The material will be most useful to newcomers to the field, but also as a review for others, specially in related disciplines, such as additive chemistry.

There may be some duplication of previous basic tribology subjects, but we believe that the Battelle report is unique and comprehensive, and that some repetition is justified.

The following is the “Preface” from the original report.

Douglas Godfrey
Contributing Editor

Many industries have long been plagued by profit-devouring problems resulting from wear: producing lines screech to a halt when equipment malfunctions, maintenance costs soar, and output quotas are not met. In fact, wear ruins hundreds of millions of dollars worth of equipment and products each year.
To curtail these losses, industry can use effective techniques resulting from tribology – the science of friction, lubrication, and wear. By integrating fluid and machine dynamics, metallurgy, physical and surface chemistry, heat transfer and stress analysis, tribology offers a systematic, broad based approach to wear control. Though still developing, tribology already can save millions of dollars by upgrading design and protection of critical machine elements – e.g., bearings, gears, cams and traction drives for such components as internal combustion engines, turbines and other commonly used devices.

Ideally, tribology techniques should be applied in the equipment design stage. Here, service life can be predicted by using recently developed computer models that can simulate operating conditions. Designers are better able to refine geometries, select suitable lubricants and develop improved lubrication supply methods. These techniques can also be beneficially applied during equipment operation for reducing noise, alleviating shock or cyclic loading, identifying lubrication problems, and developing efficient maintenance programs – thus extending service life.

But to use these techniques effectively, companies may need to initiate a program to track wear costs. While a few companies, particularly in Japan, are now instituting such programs, data gathering worldwide is sparse. With hard data in hand, companies will be able to determine priorities for best applying their wear-control dollars. And, as the science progresses, technological advances and better wear tracking methods will help companies improve equipment and product resistance to wear, thus enhancing productivity in using materials and energy.

To date, most tribological research has focused on lubrication, primarily because it has been the simplest, most available, and least expensive wear control method. Consequently, in this report, we will concentrate on the main lubrication systems – hydrodynamic, elastohydrodynamic, and boundary: what principles govern their use, and where and how they can be applied.

PART I – INTRODUCTION

Tribology: a modern science ……

Within recent years, the drive to minimize wear has focused on analysing and predicting the mechanisms that occur between interacting surfaces in relative motion. Rigorous, basic studies begun only twenty years ago have evolved into a dynamic science devoted to the study of lubrication, friction, and wear: tribology. A relatively new word in the technical vocabulary – derived from the Greek root “tribein”, meaning “to rub” – the term “tribology was coined in England in the mid 1960’s.

Today, by applying what has already been learned from basic research in tribology, wear control in our modern industrial environment can be significantly advanced – and real cost savings ca be achieved. According to a 1966 report published by the British Lubrication Engineering Working Group, the application of established lubrication principles in industry could save as much as $800 million (1) annually in Great Britain through reduced energy consumption and machinery repair alone. And in the U.S., industry spends $2.8billion (2) a year in purchasing and regrinding cutting tools – not including labour costs and machinery downtime for worn tool replacement. More recent studies in the U.S. and elsewhere – prompted by product durability concerns and attempts to conserve energy and materials **-** have resulted in similar conclusions.

Also, during the past two decades, the drive to develop advanced propulsion systems – e.g., high performance gas turbines, nuclear engines and booster rockets – accelerated the need for more sophisticated lubrication, friction, and wear technology. The nuclear and aerospace industries, in particular, faced critical problems – with ultra high-speed bearings, gears, and seals operating at high temperature, and with erosion of supersonic air foils – that could **not** be solved by conventional lubrication, bearing, or materials approaches to wear control. As a result, advanced research conducted for these systems led to new principles, and to new lubricants, designs and materials that vastly enlarged the existing store of tribological information.

…. responding to a pervasive need

An array of machine elements – without which most manufacturing processes and many products would screech to a halt – depend on tribological principles and techniques to achieve acceptable performance levels and service life. Among these are:

- Journal bearings
- Thrust bearings
- Rolling element bearings
- Ball bearings
- Gears
- Cams
- Traction drives
- Hypoid differentials
- Oscillating bearings
- Face seals

Incorporated into such vital components as internal combustion engines, turbines, compressors, and transmissions, these elements can be found in a broad spectrum of industrial process machinery, transportation and aerospace vehicles, and energy related equipment.

What tribology is

Tribology is a multidisciplinary field based on fluid and machine dynamics, metallurgy, physical and surface chemistry, heat transfer, and stress analysis. The reason: contact between sliding or rolling surfaces creates highly complex reactions that can only be understood by drawing from a range of disciplines. To better appreciate this complexity, consider the next diagram, which depicts the constituents of sliding contact.

Various lubricants have long been used, almost casually, to prevent friction and wear between surfaces. However, we now know it really isn't that simple. Movement of the surfaces causes shearing within the lubricant, producing friction and heat that are rejected through the lubricant and bearing, or other parts. Such heating also causes a reaction between the machine element's surfaces and the environment, resulting in a reaction product. Soluble phosphates in lubricant additives, for example, will produce phosphate films on steel surfaces during sliding friction. Furthermore, fluctuations in friction can lean to instability, vibration and noise. For example, surface-to-surface contact during start-up produces high contact stresses at a few small high spots, or asperities, on the surface. Adhesion, a form of wear, can occur at these contact points, causing momentary localised heavy flow of surface particles as the junctions shear.

Recognising the significance of all these processes, tribologists have incorporated them into a **system** capable of controlling wear and predicting equipment performance.

In this systematic approach, critical performance factors that may cause a wear problem are first measured and evaluated. Then, to dramatically reduce the detrimental effects of surface interaction – thereby enhancing service life and reliability – more complex strategies are applied, based on:

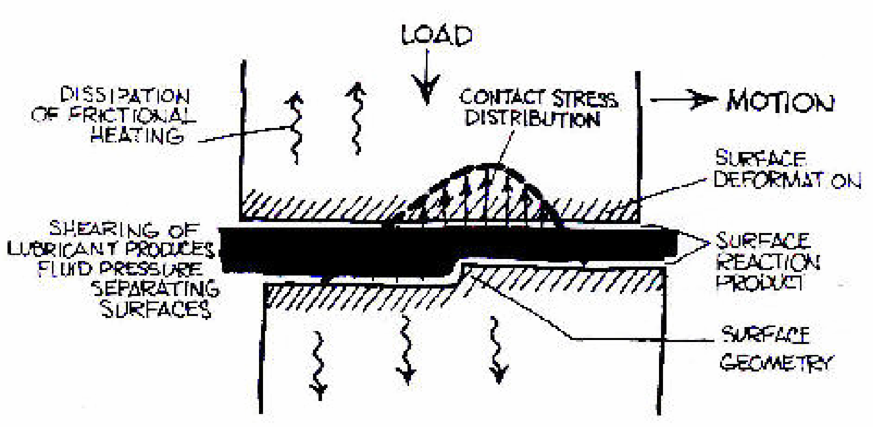
- In-depth knowledge of the basic mechanisms of lubrication so that all relevant factors can be integrated into the systematic approach
- Development of lubricants that perform under certain conditions of temperature, stress and pressure, and in particular environments for the required service period
- Refinement of designs and geometries that minimize friction and wear, as well as the amount of lubrication needed for components and assemblies
- Selection of materials that withstand a range of operating conditions

In essence, the science of tribology can be applied to

- Enhance understanding of what occurs between contacting surfaces in relative motion
- Optimise equipment performance through advanced lubrication technology – and, ultimately,
- Reduce wear and energy consumption.

Tribology systematics for industrial use

Since lubrication is the most available, understood, and frequently used key to wear reduction, the major thrust of this report will be to describe advances in lubrication technology. It also forms the basis used here for classifying tribological systems.



Processes involved in sliding contact

As body 1 approaches body 2 under a loading condition, the approaching surface and the space between them become a closely interrelated system influencing the way one body slides over another. As sliding starts, any fluid lubricant will shear and the viscous response to surface discontinuities (steps, tilt and taper) will produce pressure in the fluid. If the pressure is sufficient to balance the applied load, sliding will occur with no solid contact between the surfaces. Increasing the load will cause the fluid film to decrease in thickness and cause high spots on the surfaces to contact.

Tribological lubrication systems can be viewed – and, in part, differentiated – in terms of the amount of separation between "contacting" surfaces of machine elements. In this classification scheme, the lubrication systems are:

- Hydrodynamic
- Elastohydrodynamic
- Boundary

As seen in the graph, a fourth condition – mixed film lubrication – can also occur.
When fluid dynamic processes are capable of causing complete separation of moving surfaces, hydrodynamic conditions exist; and friction is proportional to viscosity and speed, and inversely proportional to the load.

As shown in the preceding graph, film thickness decreases with bearing pressure. For metallic bearing materials elastic deformation begins to play a role in film support at about 10,000 psi. Lubricant viscosity is affected by pressure, increasing with the increasing pressure. Thus film thickness becomes a function of the spreading of the contact area by elastic deformation, and the increase in lubricant viscosity with increasing pressure. These conditions are called "elastohydrodynamic".

When the lubricating film becomes extremely thin, high spots on the surface break through the film and contact high spots on the opposing surface. Here, contact pressures are very high and surface contact will occur principally on a very thin coating of surface reaction products. If the coating has sufficient penetration resistance, it will prevent intimate surface contact and adhesion, a form of wear. Boundary lubrication occurs under these conditions; and film thickness and friction no longer are influenced by fluid viscosity.

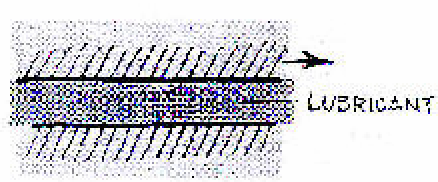
Here, we will briefly look at these principal lubrication systems and their impact on friction and wear reduction when applied to surfaces in rolling or sliding contact. In later sections of this report, each system – its purposes, principles, industrial uses, and important technological advances – will be presented in more detail.

Hydrodynamic Lubrication

Hydrodynamic conditions exist when a viscous oil film **completely** separates moving surfaces within machine elements – as in well operating journal bearings. Under these conditions, direct surface-to-surface contact does not take place, and thus wear does not occur.

For elements operating with hydrodynamic lubrication, mathematical calculations have been formulated to predict accurately

- Fluid film thickness
- Frictional losses
- Heat generation
- Safe operating limits of the lubrication system.



- **Hydrodynamic –** where surfaces are completely separated by a viscous film.

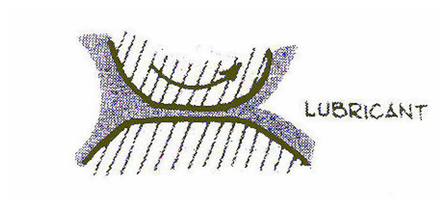
Although these idea conditions may no always be maintained throughout the entire equipment operating cycle, hydrodynamic analysis, nonetheless, can yield workable solutions to a broad group of practical lubrication and wear problems in internal combustion engines, turbines, compressors, and transmissions.

Elastohydrodynamic Lubrication

Commonly known as EHD, elastohydrodynamic lubrication also pertains to sliding surfaces, but more often involves rolling surfaces separated by an oil film. The mechanisms for oil film formation in EHD lubrication are very much like those in hydrodynamic lubrication; however, in elastohydrodynamic lubrication, the interface region between the moving parts elastically deforms under the contact pressure. This deformation creates larger oil film areas, and therefore, greater load carrying ability than that predicted by hydrodynamic theory. Elastohydrodynamics films are very thin and require polished surfaces to prevent asperity contact.

Here too, mathematical calculation can be applied to predict film thickness, frictional losses, heat generation, and safe operating limits of the lubrication system.

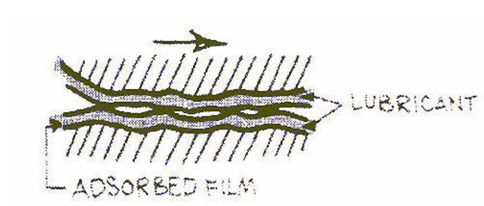
Elastohydrodynamic lubrication for wear control is typically used in rolling element bearings, gears, cams and traction drives in such equipment as jet engines, precision gyroscopes for navigation, centrifugal blowers, and transmissions.



Elasohydrodynamic*-where elastic deformation at the contact interface allows greater load carrying ability****.***

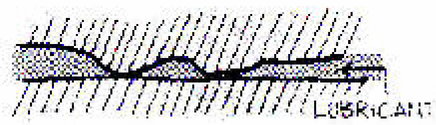
Boundary Lubrication
For slowly moving elements under heavy load, hydrodynamic and elastohydrodynamic lubricant pressures are often insufficient to separate surfaces completely. In these cases, surfaces can be protected from excessive friction and wear by absorbed films created by chemical interactions between the surfaces and the lubricant. If this boundary film is sufficiently thick, it will also prevent adhesion due to direct surface-to-surface contact. In this process – known as boundary lubrication – lubricant thickness, friction, and heat generation predictions are empirically based.

Boundary lubrication reduces friction and wear in high-load, low-speed applications and permits start-up or shutdown of hydrodynamic bearings when speeds are too slow to generate adequate films.



- ***Boundary****-where adsorbed films protect contact Surfaces exposed to show speeds or high loads*.

Mixed Film Lubrication
Apart from hydrodynamic, elastohydrodynamic, and boundary lubrication, another condition, known as “mixed film” lubrication may occur. Mixed film lubrication, as the term implies, is actually a combination of boundary and hydrodynamic or elastohydrodynamic modes. This intermediate state is attained when the oil film becomes very thin, causing asperities to penetrate the film and contact the opposing surface – i.e., the load is partially supported by a fluid film, and partially by solid contact.



- ***Mixed film lubrication****-an intermediate condition-occurs*
  In hydrodynamic or elastohydrodynamic bearings wear.

This condition is created in hydrodynamic or elastohydrodynamic bearings when

- Operating speed is too low
- Load is too high
- Lubricant viscosity is too low

Consequently, mixed film lubrication results during:

- Start-up
- Slow-down to stop
- Overloading
- Overheating

Operation in this mode typically causes bearings to wear; yet realistically, this state cannot be totally avoided. Consequently, bearing structural design must allow for operation during mixed film as well as during boundary film conditions. In addition to meticulous geometrical design, careful selection of materials can also help to compensate for operation in this mode.

In this report, mixed film lubrication will not be treated separately, but only as it relates to the total lubrication and wear process.

The table found on the following pages lists the principal lubrication systems, and some important factors that influence their use.

References:

(1) *"Wear Control to Achieve Product Durability Workshop", U.S. Office of Technology Assessment, Washington, D>C>, February 23 through 25, 1976*

(2) *Ibid.*