TRIBOLOGY FROM LEONARDO TO THE THIRD MILLENIUM;- MILLIMETRES TO NANOMETRES

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Synopsis

In this paper some of the threads of progress in the subject now known as tribology are followed from the time of Leonardo to the present day.

Major developments in the understanding of friction between the days of Leonardo and the dawn of the twentieth century are outlined, together with the shift from animal and vegetable lubricants to mineral oils in the late nineteenth century.

Particular attention is focused upon stirring developments in the science of lubrication and surface contact in the 1880's. Plain and rolling element bearing developments in the first half of the twentieth century are outlined.

Two examples of progress in tribology, namely elastohydrodynamics and friction and wear, are outlined as illustrations of recent developments.

Whereas film thicknesses in bearings at the start of the century were measured in multiples of microns, modern machinery enjoys the protection of lubricating films of nano-metre proportions. There has been a marked reduction in the wear of machine elements in recent years and current studies are exposing the transition from fluid-film to mixed and boundary lubrication and revealing the very nature of boundary lubrication.

1. Introduction

The word *tribology* was introduced into the English language in 1966 [1] to unify the individual disciplines of lubrication friction and wear. In this paper attention will be drawn to some of the significant advances made in the subject during the second half of the twentieth century, but as befits a lecture recognizing the life and work of George Sarton, the continuity of developments in tribology since the time of Leonardo da Vinci will also be outlined.

The starting date for the story is arbitrary, since our forefathers introduced impressive, pragmatic solutions to problems encountered in the development of tools, transport, machinery and construction several hundreds and even thousands of years ago.

Examples include the 4,500 year old door socket from Gudea and the nail studded tripartite wheels of a similar age from Mesopotamia. The Assyrians used sledges sliding over logs in the transport of large stone carvings some 2,700 years ago. It has been suggested that the logs were used as rollers and although the evidence for this is inconclusive, there is no doubt that water was used as a lubricant to reduce the friction and to facilitate the movement and positioning of heavy objects. Metal hoops were heated and slipped over wooden wheels to stabilize the felloe and to

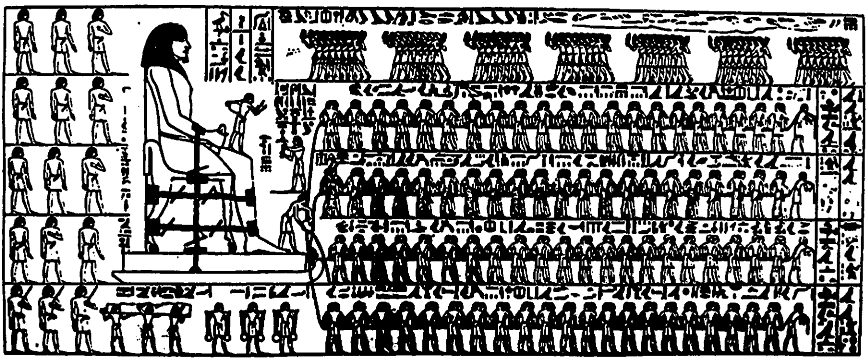

Figure 1 : Transporting an Egyptian Colossus-from the tomb of Tehuti-Hetep, El-Bersheh. (C 1880 B.C.)

reduce the wear of these important parts of carts and waggons. Horse shoes emerged in Roman times, as did the use of metal nails in shoes.

Perhaps the outstanding feature of tribological progress pre-Leonardo da Vinci was the development of early forms of cylindrical, taper roller and ball bearings. The evidence was found in Lake Nemi, in the Alban hills some 29km south east of Rome. All the rolling elements, now dated to 44 to 54 A.D., were trunnion mounted, but they represented a fascinating move towards the free rolling element bearing of modern times. There is also an indication that the Celts used wooden rollers in grooves in bronze collars on the Djebjerg cart, dating back to the first century B.C.

Medieval clocks called for the development of improved bearings and the extensive use of gears, while hard stone inserts protected the mouldboards of ploughs and the axles of carts.

This leads us to the remarkable insights into the essence of many features of tribology evident in the notebooks of Leonado da Vinci.

2. Leonardo da Vinci and Tribology

Leonardo da Vinci is perhaps better known for his art than his science and engineering, but his writings and sketching in the *Codex Atlanticus,* the *Arundel MSS. 263* and the *Codex Madrid* discovered as recently as 1967, confirm his acute recognition and understanding of many basic features of tribology. He was born in the small village of Vinci to the west of Florence, Italy, on April 15th. 1452 and he died near Amboise, France, on May 2nd. 1519.

Studies of friction are reflected in fascinating sketches of blocks of various shapes sliding on horizontal and inclined surfaces in the Codex Atlanticus and the Codex Arundel. He clearly recognized that the force of friction between sliding bodies was directly proportional to load... " *friction produces double the amount of effort if the weight be doubled*" ... and that it was independent of the apparent contact area... " *friction made by the same weight will be of equal resistance at the beginning of its movement* *although the contact may be of different breadths and lengths"*...; conclusions consistent with the laws of static friction associated with the name of Amontons [2] since 1699. He also observed that ..." *every frictional body has a resistance of friction equal to one-quarter of its weight* ". This not only introduced the concept of a coefficient of friction, it provided a fair quantitative estimate of the coefficient of friction for materials used in bearings in early Renaissance times.

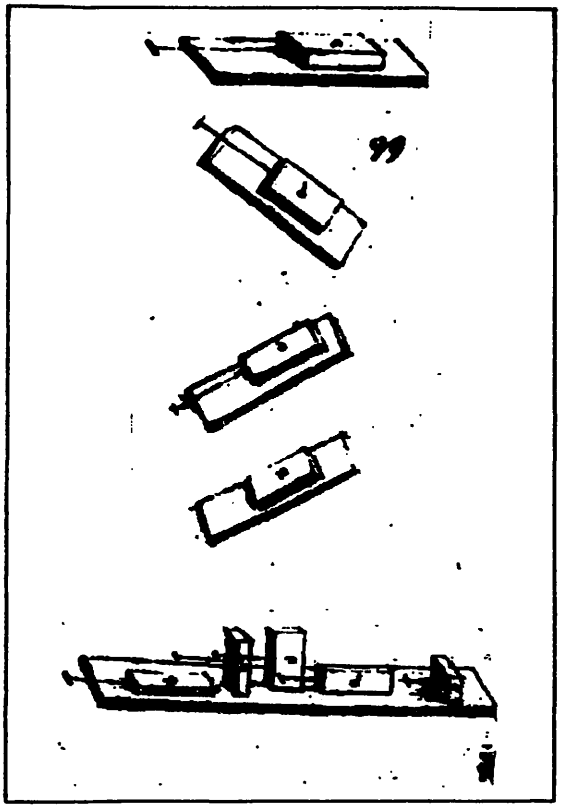

Figure 2 : Leonardo da Vinci's Studies of Friction.

Leonardo also observed the nature of wear in bearings. He sketched the form of wear grooves, recognized that wear in pulley bearings took place in the direction of the resultant load vector and that the amount of wear was related to the load. He also recommended the use of a smooth *mirror metal* or *mother* consisting of three parts of copper and seven of tin as a low friction bearing material. The advantages of rolling over sliding configurations was recognized and he sketched a number of *roller-disc* bearings which are now known to have been in use in Europe at the time. But he also went further and proposed the use of rolling bearings with free rolling balls or rollers.

He also recognized the need to introduce a bearing cage or retainer to minimise friction between the rolling elements, since he wrote... " *I affirm, that if a weight of flat surface moves on a similar plane their movement will be facilitated by inter-posing between them balls or rollers; and I do not see any difference between balls and rollers save the fact that balls have universal motion while rollers can move in one direction alone. But if balls or rollers touch each other in their motion, they will make the contact between them, because their touching is by contrary motions and this friction causes contrariwise movements*"

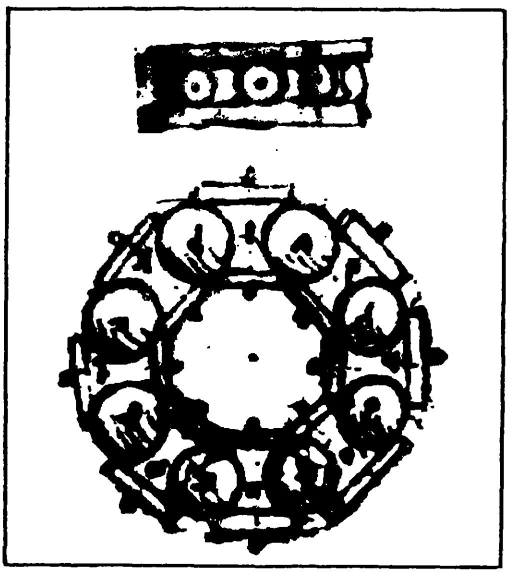

Figure 3 : Leonardo's Ball Bearing with Cage.

The sketches of simple forms of plain and rolling bearings in the notebooks of Leonardo da Vinci are truly remarkable. It is a sobering thought that these early concepts still form the foundations for modern bearings, some five hundred years after their recommendation in the writings of Leonardo.

While the above outline of Renaissance times concentrate on Leonardo's views of tribology, his greater wisdom about science and technology is exemplified by two significant quotations.

... " *Practice should always be based upon a sound knowledge of theory*"..

... " *The supreme misfortune is when theory outstrips performance*"..

3. Early Scientific Studies and Engineering Progress in Tribology (c1500-1850)

In the sixteenth century the development of wooden and metallic bearings, seals and gears benefited from an impressive growth of the mining industry. Water pumping requirements promoted advances in all these components. Books by Agricola (1556) and Ramelli (1588) richly illustrate the development of machinery during this period. It is particularly interesting to see illustrations of the roller-disc bearings sketched by Leonardo in use in sixteenth century pumps.

The general development of machinery for the printing, pottery and clock making industry also stimulated progress towards improved bearings in the sixteenth century.

The emergence of modern science was reflected in notable landmarks in tribology towards the end of the seventeenth century. It was during a discourse on carriages at the Royal Society in London on February 25th. that Robert Hooke [3] outlined his views on rolling friction. He recognized the twin contributions to rolling friction of material deformation and adhesion when he wrote... " *The first and chiefest, is the yielding, or opening of the floor, by the weight of the wheel so rolling and* *pressing; and the second, is the sticking and adhering of the parts of it to the wheel "...*

Newton's *Principia* was published in 1687 and although the hypothesis on viscous flow contained within it was associated with movements of celestial bodies, it also provided the foundation of studies of fluid film lubrication in later years.

Guillaume Amontons' [2] classical paper to the Académie Royale on December 19th. 1699 justified his studies of friction with telling references to the growing importance of machines and the effect of friction upon their performance. He wrote,.... " *among all those who have written on the subject of moving forces, there is probably not a single one who has given sufficient attention to the effect of friction in Machines"...* He was anxious to assist the engineer by making allowance for friction in the determination of forces in machinery. He suggested that the coefficient of dry friction was the same for all materials and equal to 1/3. However, a careful study of his seventeenth century manuscript shows that all his experiments were carried out with the solids coated with pork fat to ensure repeatable results-he was in fact investigating boundary and not dry friction!

Amontons envisaged friction as the force required to lift interlocking asperities over each other in sliding motion. He established the laws of static friction by recording that the force of friction was;-

1 directly proportional to the applied load.

2 independent of the apparent area of contact.

-although Leonardo had recognized the same points.

The role of asperities continued to dominate thinking on friction for many years, as evidenced by the writings of Bélidor [4] in France and Euler in Germany. The former modelled the roughnesses of surfaces by regular hemispherical asperities and his beautifully simple analysis showed that the coefficient of friction was equal to $(1/2\sqrt{2})$ or 0.35. It is interesting to note that Leonardo (0.25), Amontons (0.33) and Belidor (0.35) all proposed very similar values for the coefficient of friction for sliding materials.

Further studies of friction introduced the concept of *'cohesion'* (Desaguliers [5]) as a contributing factor to friction, but the mechanistic view prevailed for many years.

The roller disc bearings sketched by Leonardo and employed on fixed machinery in the sixteenth century were applied to waggons and carriages and called friction wheels by Jacob Rowe [6] in 1734. Free rolling cast iron balls were also introduced into bearings on fine carriages by Varlo as early as 1772 and the influence of road vehicle development on bearing technology was clearly evident at that time. Cast iron balls were also introduced into large thrust bearings for wind mills at about the same time.

The outstanding contribution to the subject of friction in the eighteenth century was undoubtedly the work of Charles Augustin Coulomb. There was growing concern for the effect of friction upon machine performance and, in particular, upon ship construction. Pulleys and capstans were inefficient and ships sometimes stuck on slipways at launching ceremonies. The Academy of Sciences offered a prize for original work on the subject and Coulomb responded to the challenge from his position in the arsenal at Rochfort. He tested a wide range of material combinations in a specially constructed friction apparatus and confirmed Amontons' laws. In addition his studies of friction during motion established the third law of friction;-

3 Kinetic friction is independent of sliding velocity.

Coulomb provided an explanation of this additional feature of friction by relating it to the deformation of interlocking asperities, thus confirming the established view of the role of asperities in determining friction.

Early in the nineteenth century doubts were beginning to arise about the purely mechanistic concept of friction linked to asperities and the force required to lift them over each other. It was the thermodynamicist, Leslie [7] who pointed out that friction did not disappear on smooth surfaces. He paid attention to the time dependent aspects of friction and introduced the concept of a deformation process in the phenomenon of friction.

The tussle between supporters of the interlocking asperities and the deformation loss schools of thought continued until the present century, but in due course it was recognized that adhesion, material deformation and asperity interactions could all contribute to the friction process. Friction was by far the most extensively addressed aspect of tribology in the early centuries of scientific study. A more complete account of the history of studies of friction can be found in [8]

The growth of industrialisation in the nineteenth century, and particularly the exploitation of mineral oils and the rapid expansion of the railways, focused attention on lubricants and lubrication, with wear studies being predominantly a twentieth century field of study. The subjects of lubrication and wear have attracted much attention in the second half of the twentieth century.

4. Lubricants and Lubrication

Vegetable oils, animal fats and water were all used to reduce friction and wear in the ancient civilizations. Leonardo recognized the role of lubricants in determining friction since he wrote that friction was affected... *"when any greasiness of any thin substance is interposed between the bodies that rub together "*... Empirical development of lubricants was promoted by the increasing demands of machinery, with light mineral oils being used in lightly loaded bearings in precision instruments such as clocks, and animal fats in larger, more heavily taxed machinery such as water wheels and windmills.

Exploitation of mineral oils in Scotland and Canada and particularly in the USA and Russia in the mid- nineteenth century changed the scene remarkably. Vegetable and animal oils were largely displaced and replaced by the readily available mineral oils; a situation that persists today, even though synthetic fluids are now increasingly finding application for specialist requirements. A good historical marker for the start of the oil age is August 27th, 1859, when Colonel Drake struck oil at Titesville in North

Western Pennsylvania. The versatility of refined mineral oil with the lighter fractions being used for illumination and the heavier constituents for lubricants was quickly recognized, although it took some time to persuade all engineers that the oil from rocks was as efficacious as the well established vegetable and animal products.

5. The Golden Decade of the 1880's

Perhaps the most remarkable progress in the long history of tribology was reported in the 1880's.

Heinrich Hertz [9] derived the equations for dry contact stresses and deformations between elastic bodies while working with Helmholtz on electrical problems in Berlin. He attended a meeting of the Physical Society of Berlin at which Newton's rings were demonstrated and he began to wonder about the influence of the load on the shape of the lenses which were pressed together to demonstrate interference patterns. He solved the problem during the Christmas vacation in 1880 and read his now classical paper to the Physical Society in Berlin in January 1881. His work was to provide the essential basis for developments in the rolling element bearing industry and indeed of stress and deformation calculations for many non-conforming machine elements, such as those encountered in gears, cams and seals in subsequent years.

The regular failure of railway axle boxes prompted Beauchamp Tower [10] in England and Nikolai Pavlovitch Petrov [11] in Russia to undertake independent studies of friction and lubrication in these vital machine elements. Tower's work was promoted by the Institution of Mechanical Engineers, following an investigation of research priorities. He detected pressures within the bearing well in excess of the mean pressure required to support the load and concluded that... " *In a well lubricated bearing the brass actually floated on a film of oil such that the pressures within certain parts of the film considerably exceeded the mean pressure due to applied load* "...

Petrov was concerned to improve the performance of railway axle boxes, but he also wondered if the Caucasian petroleum products could be utilized in this application. He held the Chair of Steam Engineering and Railway Vehicles in the Technological Institute in St. Petersburg. He was one of the first to draw attention to the economic aspects of tribology, since he noted that Russia spent millions of roubles on fuel for machinery, and imperfect lubrication could therefore cost the country gigantic sums of money if it involved a 5 or 10 per cent increase in fuel consumption. He conducted no less than 627 experiments on a specially designed railway axle friction measuring machine and concluded that the friction was determined by the viscosity of the oil. The hydrodynamic nature of axle bearing friction was thus established and reported independently by Tower and Petrov in 1883.

It is worth noting that Hirn [12] had previously reached similar conclusions from his carefully conducted friction experiments in 1854. He tested fats, mineral oils, water and air and found that the friction was directly proportional to the lubricant viscosity if the temperature of the bearing was held constant. His results were so contrary to the well known laws of friction established by famous French predecessors such as Amontons, Coulomb and Morin, that they received little support and recognition. Neither the Académie des Sciences in Paris nor the Royal Society in London deemed his work worthy of publication.

Professor Osborne Reynolds of the University of Manchester had clearly distinguished between laminar and turbulent flow shortly before hearing of Tower's observation that a film of lubricant separated the bush from the journal. He applied the principles of slow viscous flow to the problem and published his classical paper and the most famous equation (5.1) in tribology in 1886 [13].

$$\frac{d}{dx}\left[h^3\frac{dp}{dx}\right]+\frac{d}{dy}\left[h^3\frac{dp}{dy}\right]=6\eta\left\{(U_o+U_h)\frac{dh}{dx}+2W_1\right\} \tag{5.1}$$

Reynolds appears to have presented, but not published, his equation governing fluid film lubrication at the British Association Meeting in Montreal in 1884. The full paper, extending to some 77 pages, was published in the Philosophical Transactions of the Royal Society.

Equation (5.1) forms the basis of fluid film bearing analysis and design to the present day. It was soon accepted that successful, load supporting hydrodynamic action called for the formation of a convergent oil film in the direction of lubricant entrainment; a feature which became known as the 'wedge' principle.

Interest in bearings and lubrication was not restricted to Europe in the latter years of the nineteenth century. Robert Henry Thurston, who became the first President of the American Society of Mechanical Engineers, published his famous book on ' Friction and Lost Work in Machinery and Millwork' in 1885. The book, which ran to seven editions and was reprinted as late as 1907, was dedicated to Hirn. It had a great impact upon late nineteenth century attitudes to the subject now known as tribology.

The fundamentals of both dry contact and fluid film lubrication and a recognition of the growing importance of the subject were thus presented in the space of a few years in the golden decade of the 1880's. By the end of the nineteenth century major Bearing Companies were being formed and the Oil Industry was established in the U.S.A., Russia and the East.

6. Bearing Developments in the First Half of the Twentieth Century

The most spectacular development early in the 20th. Century was the introduction of the tilting pad bearing. Kingsbury devised and built the first tilting pad bearing in the U.S.A. in 1898 after reading Osborne Reynolds' classical paper. However, Michell [14] in Australia independently conceived the idea, solved the governing Reynolds equation and patented the bearing in 1905. Kingsbury [15] was finally awarded a patent in 1910.

This delightfully simple concept, designed to take advantage of the recently exposed principle of fluid-film lubrication and to operate reliably and efficiently under all conditions is a fine example of engineering design at its best. The essential features of the bearing are shown in Figure 3.

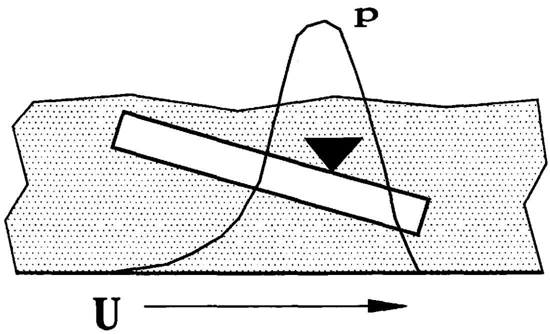

Figure 3 : Tilting Pad Bearing

The economic impact was impressive, with marine applications alone in 1918 saving the United Kingdom a sum equivalent to £10.9m in 1996 prices.

Journal bearings automatically present a convergent-divergent clearance space and hence satisfy the wedge principle noted earlier.

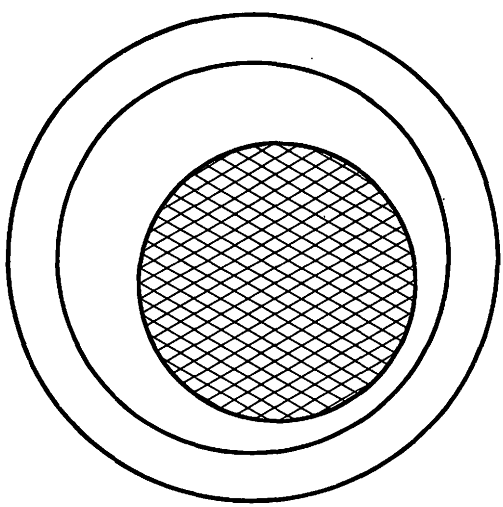

Figure 4 : Journal Bearing Geometry

As confidence in the predictions of theory developed, improved bearings were designed and major specialist plain bearing companies were formed during the first half of the twentieth century. By mid-century numerical solutions to the full Reynolds equation (5.1) were becoming available and this enabled factors such as cavitation in the divergent clearance space, the finite length of the bearing and dynamic loading such as that encountered in reciprocating engines in cars to be taken into consideration. Babbitt materials dominated the plain bearing field throughout most of this period, but increasing loads on engine bearings prompted the development of copper-lead alloys to enhance strength while preserving the excellent characteristics of babbitt.

In the field of lubrication the most notable event was the recognition of a second major form of lubrication by Sir William Bate Hardy (16). When fluid-film lubrication can no longer keep the opposing surfaces apart by hydrodynamic action owing to excessive loading or very low speeds, at least some of the load is supported by direct contact between opposing solid surfaces. The friction under these conditions is determined by the surface layers or films formed by physical adsorption or chemical reaction between constituents of the lubricant and the solids. These surface films, which may be of molecular proportions, provide excellent protection to the bearing solids. Hardy named this mechanism 'boundary lubrication'.

Stribeck (17) investigated journal bearing friction and portrayed the three major regimes of lubrication on a chart now known as the Stribeck diagram. The friction was found to be dependent upon a parameter (S), named after Sommerfeld, defined as,

$$\mu = f\{S\} = f\left\{\left(\frac{c}{R}\right)\left(\frac{\eta R \Omega l}{W}\right)\right\} \qquad (3)$$

The very useful clarification of lubrication regimes which emerged from this study is portrayed in Figure 5.

Major ball and roller bearing Companies were established in Europe and the U.S.A. to underpin the development of rail and road vehicles. The technology was supported by impressive engineering science based upon the studies of Hertz (9), Stribeck (17) and Goodman (18). The influence of manufacturing accuracy, surface finish and the quality of materials upon the life of rolling element bearings was investigated. Palmgren (19) found that the life (L) was related to load (W) by the simple relationship,

(4) $$W^3 L = constant$$

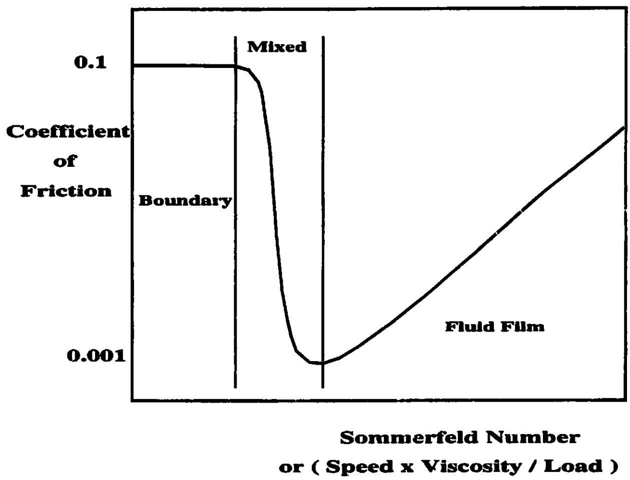

Figure 5 : Stribeck Chart

Interest in surface roughness and surface topography in general fostered the development of profileometry by Abbott and Firestone (20) in the University of Michigan in 1933.

A theoretical basis for adhesive friction also emerged in the first half of the twentieth century, with contributions from Prandtl, Deryagin, Holm and Bowden and Tabor (21). The latter developed an appealingly simple concept as follows. Imagine the contact between asperities shown in Figure 6, where the force of friction represents the effort required to break adhesive junctions of total area 'a' generated by the applied load (W).

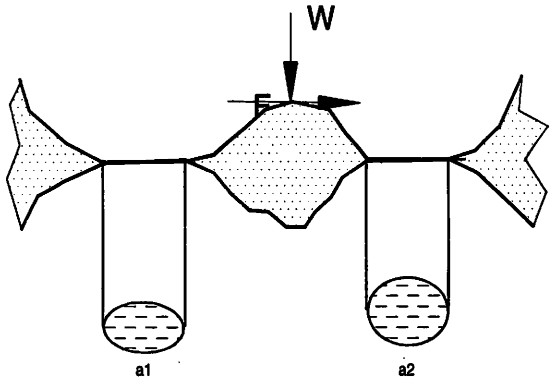

Figure 6 : Adhesive Friction

If (s) and (H) represent the mean shear stress and the Hardness of the softer material respectively,

$$(5) \qquad \mu = \frac{F}{P} = \frac{as}{aH} = \frac{s}{H}$$

Deryagin (22) had previously proposed a binomial expression for friction which incorporated both the normal stress developed by the applied load (p) and that attributable to adhesion between molecules on the opposing surfaces (p_o) .

$$(6) \qquad \mu = \frac{F}{\alpha\ (p + p_o)}$$

By the mid-twentieth century the essential difference between fluid-film and boundary lubrication had been identified, plain bearing analysis, design and manufacture were well advanced, reasonably reliable and cheap ball and roller bearings had become available in vast quantities and the mathematical formulation of adhesive friction had been presented.

7. Tribology in the Second Half of the 20th. Century

I will select just two aspects of the science and technology of tribology to illustrate progress in recent times; Elastohydrodynamic lubrication and Friction and Wear.

7.1 Elastohydrodynamic Lubrication

Whereas the continuum fluid mechanics approach of Osborne Reynolds (13) had satisfactorily explained the functioning of plain bearings and enabled adequate design procedures to be developed for most bearing forms encountered in modern machinery, it had failed to explain how highly stressed components such as gears, ball and roller bearings, cams and certain seals were lubricated. In essence, solutions to the Reynolds equation failed to predict adequate film thicknesses, compared to the surface roughnesses in such bearings, even though operating performance was indicative of fluid-film rather than boundary lubrication action.

The quandary was resolved, primarily as a result of work in the U.S.S.R. and the United Kingdom, when it was demonstrated that local elastic deformation of the solids and pressure-viscosity characteristics of the lubricant greatly enhanced the potential for fluid film lubrication. A representative film shape and pressure distribution for nominal line contacts is shown on Figure 7.

Simultaneous numerical solutions to the Reynolds and the elasticity equations developed and by the mid-1970's it was possible to calculate the minimum film thickness in point or line elastohydrodynamic conjunctions with acceptable accuracy. The main findings were that the calculated elastohydrodynamic film thicknesses [23], using equations like (7), were much bigger than those for hydrodynamic lubrication alone, being typically ten to a hundred times greater. It was found that films of about one micron could be sustained and this readily explained why such highly loaded lubricated contacts as gears enjoyed the benefits of fluid film lubrication.

(7) $H^*_{min} = 3.63\, U^{0.68}\, G^{0.49}\, W^{-0.073}\, (1 - e^{-0.68k})$

where; $H^* = (h/Rx)$; $U = \eta_o U/ E^1 R_x$;

$W = (w/E' R2x)$ and $k = (a/b)$.

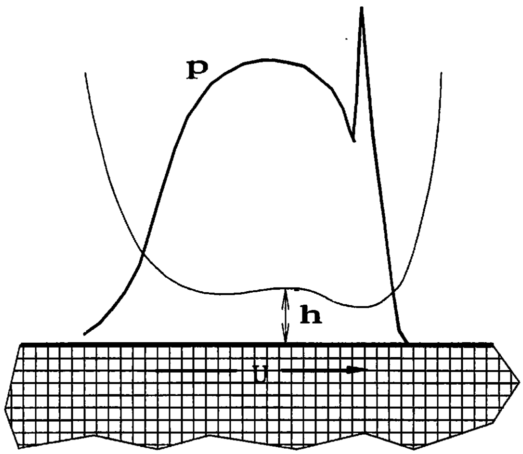

Figure 7 : Elastohydrodynamic Line Conjunction

Once the predictions of film thickness had been proved to be reliable, they were introduced into design procedures for gears and rolling element bearings. The ratio of the calculated elatohydrodynamic film thickness to the composite surface roughness, known as the 'lambda' ratio, proved to be indicative of resistance to surface fatigue in rolling elements. It was found that a ratio in excess of 2 or 3 could greatly extend the life and this was attributed to a minimisation of the ill effects of asperity contacts.

For lambda ratios of about unity, a good deal of asperity contact could be anticipated, but there were nevertheless situations in which effective elastohydrodynamic films offered protection, even under these severe conditions. In due course this was shown to result from local asperity deformations by the hydrodynamic effects surrounding asperities; a phenomenon known as micro-elasto-hydrodynamic or asperity lubrication. The action was first studied in relation to low elastic modulus materials such as seals and natural synovial joints, but it is now believed that it can be effective, under certain conditions, in protecting surfaces of higher elastic modulus, such as the metals encountered in gears, cams and rolling bearings.

An illustration of the effective smoothing of a sinusoidal surface roughness on a soft material representative of the articular cartilage found in synovial joints is shown in Figure 8.

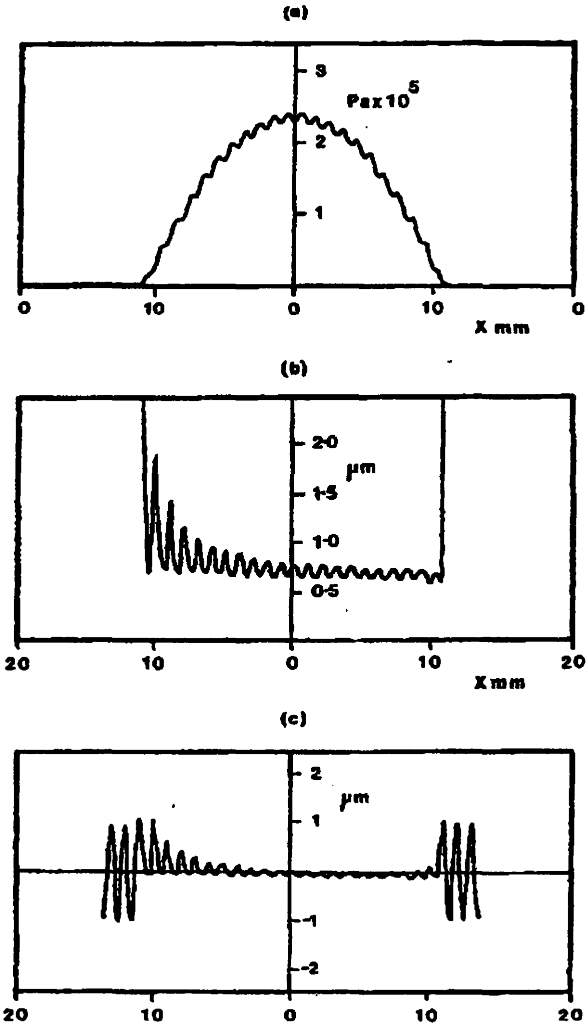

Figure 8 : Micro-Elasto-Hydrodynamic Lubrication

While the prediction of film thickness in elastohydrodynamic conjunctions appeared to be satisfactory, there was growing evidence throughout the 1980's and early 1990's that the prediction of friction or traction in such conjunctions was totally inaccurate. The reason for this was that the original analysis assumed the lubricant to be a Newtonian fluid, whereas real lubricants exhibit strongly non-Newtonian characteristics under the severe conditions encountered in gear and roller bearing conjunctions. This is hardly surprising when it is recalled that the lubricant enters the conjunction at atmospheric pressure and modest shear rate, is pressurized to one or two GPa and possibly shear rates of the order of 10^6 1/s, and then ejected back into the atmosphere after only 0.1 to 1 milli seconds!.

The shear thinning characteristic of lubricants, in which the effective viscosity decreases as the shear rate increases, can be represented in a number of ways. Johnson and Tevaarwerk [24] adopted an Eyring model of fluid flow (equation (8)), while Bair and Winer [25] proposed a logarithmic function and the concept of a limiting shear stress (equation (9))

(8) $$\frac{d\gamma}{dt} = \frac{1}{G}\frac{d\tau}{dt} + \frac{\tau_o}{\eta_o}\sinh\left(\frac{\tau}{\tau_o}\right)$$

(9) $$\frac{d\gamma}{dt} = \frac{1}{G}\frac{d\tau}{dt} + \frac{\tau_L}{\eta}\ln\left(\frac{1}{1-\frac{\tau}{\tau_L}}\right)$$

The latter model was later simplified through the use of an inverse hyberbolic tangent representation.

The limiting shear stress is itself a function of pressure and temperature. To a first approximation, the relationship can be written as;

(10) $$\tau_L = \tau_o + \gamma p$$

The shear stress transmitted through the lubricant approaches the limiting value (τ_L) at high shear rates under isothermal conditions. Since the heat generated within the film also increases as the shear rate increases, the combined effect of non-Newtonian and thermal action results in a maximum value of shear stress being attained, followed by a decrease as the shear rate increases further as shown in Figure 9.

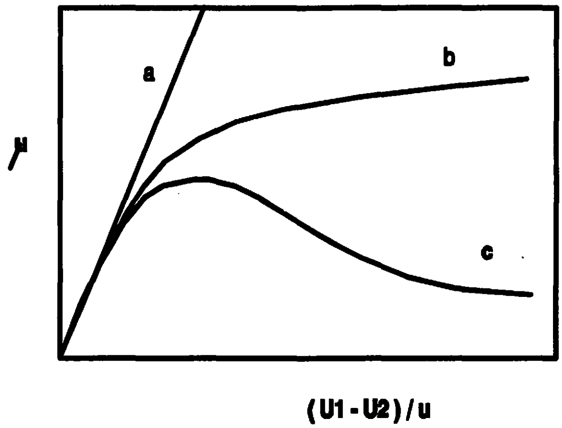

Figure 9 : Traction Curves
(a) Newtonian (b) Non-Newtonian
(c) Non-Newtonian / Thermal

Another intriguing feature of lubricant rheology in some elastohydrodynamic conjunctions is that the lubricant can 'solidify' as it passes the glass transition point within the high pressure zone. The assumption that the lubricant remains in the liquid state as it passes through the conjunction may thus no longer be tenable.

Some remarkable observations from interferometry experiments by Kaneta (26) and subsequent multi-grid, multi integration analysis by Ehret et al (27), suggests that the lubricant moves through the conjunction as a plug of solidified material, with thin shear bands between the core and the surfaces of the solids. The thin shear bands are likely to be of molecular proportions and much of the energy dissipation will take place in these regions. A representative velocity distribution across the elastohydrodynamic film under these conditions is shown in Figure 10.

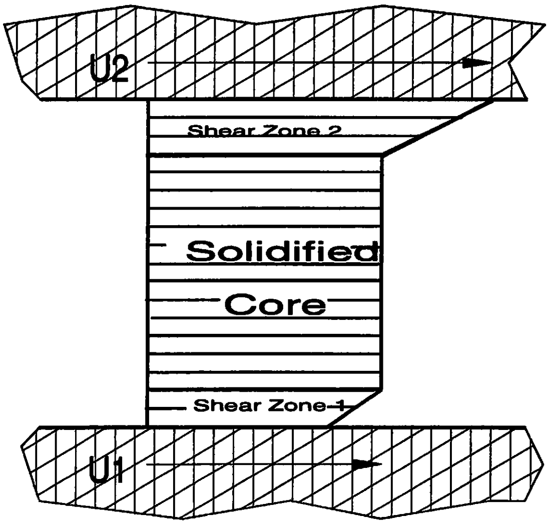

Figure 10 : Solidified Lubricant Core Flow

An interesting feature of the unfolding story of elastohydrodynamic lubrication is that it is now clear that the phenomenon persists at much smaller film thicknesses than originally envisaged. When the first theoretical solutions to the problem emerged about forty years ago, the experimental and operating film thicknesses were about 1μm. Laboratory studies on optical interferometry equipment have since shown that the equations derived in the 1960's and 1970's are valid down to films of nano-metre proportions. This marks the very limits of continuum mechanics and represents the transition to boundary lubrication. Indeed, Spikes (28) and others have shown that additives in the lubricant sustain the film thickness at a few nano-metres, representing either layers of fluid of enhanced viscosity or boundary films of molecular proportions. I have referred elsewhere (29) to this phenomenon, depicted in Figure 10, as 'the thinning film'.

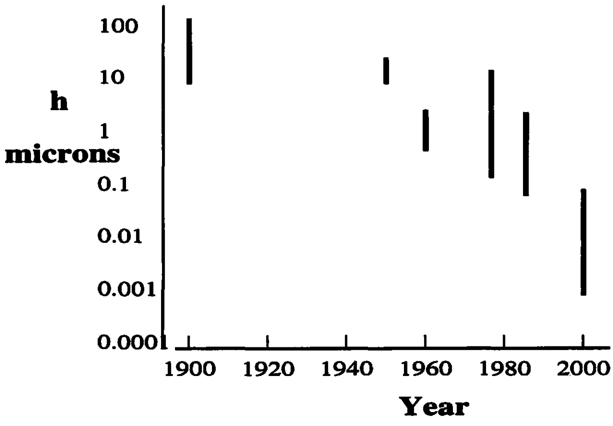

Figure 10 : The Thinning Film

7.2 Friction and Wear

Our understanding of the fundamentals in both fields has been enlarged by a greater recognition of the details of material deformation and fatigue. In the mid-twentieth century, theoretical models for the adhesive and abrasive models of friction and wear were in good accord with experience. In recent decades there has been a growing recognition of the importance of strain accumulation in the wear process, both for metals and polymers.

Recent contributions to knowledge of wear have included the concept of fatigue (Kragelski (30);delamination (Suh (31)); chemical or oxidative wear (Quinn, Sullivan and Rowson (32)); the wave model (Challen and Oxley (33)) and low cycle fatigue; shakedown (Johnson (34)); ratchetting (Kapoor and Johnson (35)) and third body wear (Godet (36)).

New insight into the phenomena of friction and wear emerged with the presentation by Challen and Oxley (33) and Black et al (37) of their wave model of friction and wear depicted in Figure 11. In this model, friction is associated with the force required to push a wave of plastically deformed softer material ahead of hard asperities. For small asperity angles, friction could occur without wear, while at larger angles, a cutting action and chip formation ensued.

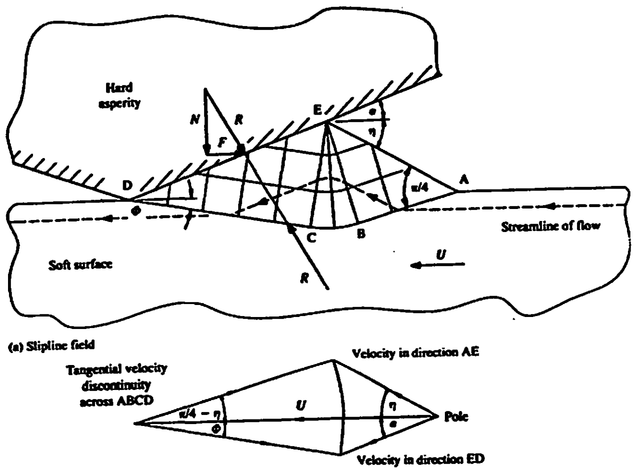

Figure 11 : Wave Model of Friction and Wear
(Challen and Oxley (33)

This model was linked to a low cycle fatigue criterion for wear, while Johnson and his colleagues (28) drew attention to the shakedown concept in which initial plastic deformation was followed by purely elastic behaviour. This group then developed a ratchetting model for the production of laminar wear debris.

The new range of laboratory instruments for the detection and measurement of friction at the atomic scale have changed our understanding of friction. Two particular instruments, the Surface Force Apparatus (SFA) and the Atomic Force Microscope (AFM) have enabled nano-scale measurements of friction to be made. Observations indicated that the irreversibility of bringing atoms together and then separating them played a bigger role in the friction and wear process than the action of adhesive bonding and the subsequent shearing and plucking out of material from the surfaces. Tomlinson (38) had proposed a link between friction and interacting atoms as early as 1929 and the concept has been rejuvenated in recent years. It now appears that the work done by friction is linked to sound and eventually heat promoted by the vibrations of atomic lattices.

Little attention was given to the influence of wear particles on the wear process itself until Godet (36) addressed the issue in some detail. Since wear particles will slide or roll between rubbing solids, it is clear that they will act as an intermediate layer and transmit at least some of the applied load. This could well modify traditional views of wear mechanisms between interacting solids. The concept of 'third body wear' has now become well established.

All these advances in the basic understanding of wear have been paralleled by remarkable improvements in the performance of rubbing surfaces in machinery. Components in vehicle engines wear at a much lower rate than was evident even twenty years ago; tyres last much longer than before; total replacement hip joints now being inserted have projected survivorships which enable younger patients to benefit from the operation without the need for further 'revision' surgery.

New technologies in the aerospace, nuclear and information fields have benefited from the skill of the tribologist. For example, in video recorders, where a limited, controlled rubbing between the head and the tape is necessary for self cleaning, wear rates are about one atomic layer per one hundred metres of tape transit!.

Many of these advances have been achieved through a better understanding of lubrication and developments in lubricant technology, through greatly improved manufacturing procedures and through the developments of materials. Surface engineering has become a vital aspect of technology, with improved surface treatments and new surface coatings greatly enhancing the wear resistance of components. Diamond like coatings (DLC) have been attracting much attention in many fields of application in recent years.

8. Conclusions

The study of interacting surfaces in relative motion, or tribology, provides a most remarkable example of multi-disciplinary studies. Much is known about the bulk behaviour of solids and liquids, but there are still many unresolved problems involving the surfaces and interfaces.

Major problems now under review include the transition from full fluid film lubrication through the mixed regime to boundary lubrication and the very mechanism of boundary lubrication itself. The detailed contributions of the solids, in bulk and at the surfaces, to the phenomena of friction and wear is actively under review.

The scale of the phenomena under study has reduced from micron to molecular dimensions in recent decades. The science of tribology is now very much under the nano-metre spotlight.

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