WEAR MODELING AND WEAR MAPPING: A REVIEW

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Abstract—Researches on the wear of metals have brought new understanding and advanced major concepts of tribology. The availability of new testing methods and instruments have made possible the detailed study of the microstructure, nanostructure, and compositions of contact surfaces. Earlier work was concentrated on the mechanics of solid contact, understanding the true area of contact, asperity plasticity, and transfer during sliding. The scanning electron microscope and the atomic force microscope have provided fascinating insights and detailed information on surface structure. There have also been developments in computational modelling of wear by finite element methods, molecular dynamics, and fracture mechanics. Many wear models and equations in the literature have been developed. No single predictive equation or group of limited equations have been found for general and practical use. Various regimes of mechanical and corrosive wear for any particular pair of rubbing materials can be shown on a single wear map plotted on axes of normalised pressure and sliding velocity. In principle the map can be divided into areas corresponding to different wear regimes, with boundaries of sliding speed and contact pressure beyond which a purely mechanical view of wear would be grossly in error, owing to the effects of oxidation.

Keywords—Tribology, Wear mechanism, Wear models, Wear equations, Wear mapping.

I. INTRODUCTION

1.1 Tribology

Tribology is the science and technology of friction, wear and lubrication. It studies the interaction of surfaces in relative motion. It concerns the understanding of a wide range of applications, from simple everyday products to complex industrial machinery and also from the artificial human joint to the aerospace journal bearing [1]. Tribology demonstrates its importance by reducing material use and energy loss.

A tribosystem consists of two bodies in contact, a lubricant in between them and environment. In a tribosystem, operating conditions, such as, normal force, sliding velocity, type of motion, contact time or sliding distance and temperature play an important role. The conditions strongly interact with the structural parameters of the tribosystem. These structural parameters are properties related to the mechanical and thermal behaviour of the material in the tribosystem and include: composition, roughness, elastic modulus, hardness and reactivity of the surfaces [2]. With a certain specific geometry of the bodies e.g. cylinder or sphere, tribological contact can be line, circular or elliptical contacts. The type of motion is also important, e.g. rolling and/or sliding motion; continuous or reciprocating motion.

The study of tribology revolves around the friction, wear and lubrication phenomena in between the contacting surfaces at macro to atomic scales [3]. Hence the study of tribology comprises a system with interacting bodies, environment and operational/process conditions at different length scales.

1.2 Contacts between Rough Surfaces

Surfaces contain roughness, i.e. deviations from the mean line and can be characterized by an arrangement of individual asperities with a different shape and size.

When two nominally flat rough surfaces are brought into contact, the contact takes place on a micro-level with each other, contact occurs only at the peak of surface features (asperities). The real

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contact area, occurring at the surface is generally less than the nominal contact area. The real contact area depends on load, roughness, material properties (hardness, elastic modulus, etc.) and type of material deformation (elastic, plastic) [2]. The ratio of the real contact area to the nominal contact area is known as the fractional contact area or the degree of contact, \( \alpha \). The development of the contact area depends on the material properties, contact load, surface roughness and presence of lubricant. The initial roughness of the surface changes due to plastification of the asperities during deformation. The asperity deformation can also be influenced by the subsurface stresses during the bulk deformation process. The asperity deformation and interaction between the asperities during the sliding motion determines the contact and friction behaviour.

The question which remains is; what is the size of the real contact area. There have been many attempts to model and estimate the real contact area [2].

1.3 Friction

Friction generated in the real contact area is a complex phenomenon associated with a variety of different physical, mechanical, and chemical processes.

The friction force can be defined as the tangential force that takes place at the surface between two contacting bodies and is directed opposite to the relative velocity between those interacting bodies. The coefficient of friction (COF) is expressed as follows:

\[
\mu = \frac{F}{N}
\]

Where \( \mu \) is the coefficient of friction, \( F \) is the friction force, \( N \) is the normal force. Generally, friction obeys the following three empirical laws (Hutchings, 1995) [2, 4]:
1. The friction force is proportional to the normal load.
2. The friction force is not dependent on the apparent contact area.
3. The friction force is nearly independent of the sliding velocity, temperature and roughness as soon as motion has begun.

Friction is a complex phenomenon which is hard to predict by knowing only some material properties and operating conditions. The coefficient of friction depends on many factors such as surface roughness, lubricant, surface chemistry, contact stress, environment, temperature, sliding speed etc.

There are many applications, specifically in sliding and rotating components such as bearings and seals, where friction is undesirable and needs to be minimized in order to avoid loss of energy and material. Hence, it is of great interest to design surfaces with low friction for those applications [2].

1.4 Wear

Wear can be defined as the removal of material from solid surfaces by mechanical action. Wear is the progressive damage and material loss which occurs on the surface of a component as a result of its motion relative to the adjacent working parts, has far reaching economic consequences which involve not only the costs of replacement but also the expenses involved in machine downtime and lost production. As a result, considerable efforts have been expended on the development of theories and deterministic models [5].

Although wear can often be reduced by liquid lubrication, there are certain applications in which liquid lubricants are not stable and a dry contact is used. Since the 1970s, wear research increased significantly in response to a technological demand for new materials with longer lifetimes and enhanced performance levels in harsh environments. Furthermore, a negative consequence of wear is not just the need to replace some mechanical parts and the cost this entail; one of the most important negative effects of wear is the cost associated with the maintenance of production processes. Many materials have been evaluated for wear resistance under dry wear conditions, and
the successful candidate materials have been tested in simulators and through component testing under field conditions [2].

1.5 Wear Mechanisms

Understanding of wear mechanisms is very important in order to design materials which are suitable for wear reduction.

Wear can appear in many ways, depending on the material of the interacting contact surfaces, the operating environment, and the running conditions. In engineering terms, wear is often classified as either mild or severe [6]. Whatever the nature of the particular materials involved, the simplest classification of unlubricated surface interactions is into those involving either mild or severe wear. This is not based on any particular numerical value of wear rate but rather on the observation that increasing the severity of the loading (by increasing the normal load, sliding speed or bulk temperature) for any pair of materials leads at some stage to a comparatively sudden jump in the wear rate. Such jumps or nonlinearities in wear behaviour or in material response have significant practical consequences for engineering designers. From a practical engineering point of view, mild wear might well be considered acceptable whereas the transition to severe conditions often represents a change to commercially unacceptable values [5]. Engineers strive for mild wear, which can be obtained by creating contact surfaces of appropriate form and topography. Choosing adequate materials and lubrication is necessary in order to obtain mild wear conditions. However, in order to get mild wear we often have to harden and lubricate the contacts in some way. Lubrication will often reduce wear, and give low friction. Mild wear results in smooth surfaces. Severe wear may occur sometimes, producing rough or scored surfaces which often will generate a rougher surface than the original surface. Severe wear can either be acceptable although rather extensive, but it can also be catastrophic which always is unacceptable. For example, severe wear may be found at the rail edges in curves on railways.

However, Barwell (1983) [8] has pointed out that the classification ‘mild’ and ‘severe’ can be very misleading, in that the rate of material loss in a ‘mild’ wear regime can be substantially higher than that in a ‘severe’ wear regime. Barwell suggested that the terms ‘mild’ and ‘severe’ apply to the form of surface damage rather than the rate of material loss.

Severe wear is associated with contact fracture; mild wear is associated with localized plastic flow and tribochemical wear [2].

Mild and severe wear are distinguished in terms of the operating conditions, but different types of wear can be distinguished in terms of the fundamental wear mechanisms involved, such as adhesive wear, abrasive wear, corrosive (or tribochemical) wear, and surface fatigue wear.

1.5.1 Adhesive wear

Adhesive wear is caused by the surface interaction and welding of the asperities junctions at the sliding contact. This wear mechanism is affected by the bonding type (ionic, covalent, metallic and van der Waals) in the contact junction. The weaker part of the materials in contact is removed and transferred to the counter surface, if the bond in the junction is stronger than the bond in the bulk. Surface removal results in a rough appearance and a large volume of worn material, hence severe wear [2].

The adhesive wear is influenced by the following parameters characterizing the bodies in contact [7]:

1. Electronic structure
2. Crystal structure
3. Crystal orientation
4. Cohesive strength

Adhesive wear occurs due to adhesive interactions between rubbing surfaces. It can also be referred to as scuffing, scoring, seizure, and galling, due to the appearance of the worn surfaces. Adhesive wear is often associated with severe wear, but is probably also involved in mild wear [6].
1.5.2 Abrasive wear

The term ‘abrasive wear’ covers two types of situations: (1) Two-body abrasion (2) Three-body abrasion. In each of which a soft surface is ploughed by a relatively hard material. In two-body abrasion a rough hard surface slides against a relatively soft opposing surface, whereas in three-body abrasion rough hard particles trapped between the two sliding surfaces cause one or both of them to be abraded [8].

Abrasive wear is the removal of material when hard asperities or particles slide over/between two surfaces in relative motion. If a hard asperity or particle moves against a softer surface, the surface deforms plastically and grooves are produced in the surface. Accordingly, wear debris can be generated by micro cutting [2]. Abrasive wear occurs when a hard surface or hard particles plough a series of grooves in a softer surface. The wear particles generated by adhesive or corrosive mechanisms are often hard and will act as abrasive particles, wearing the contact surfaces as they move through the contact [6].

The ability of the material to resist abrasive wear is influenced by the extent of work-hardening it can undergo, its ductility, strain distribution, crystal anisotropy and mechanical stability [7].

1.5.3 Fatigue wear:

The relative motion of the surfaces in contact is composed of varying degrees of pure rolling and sliding. Continued load cycling eventually leads to failure of the material at the contacting surfaces [7]. Wear debris is generated by cyclic loading of the contact. Fatigue wear can be characterized by crack formation and flaking of surface material [2].

Surface fatigue wear can be found in rolling contacts, appears as pits or flakes on the contact surfaces; in such wear, the surfaces become fatigued due to repeated high contact stresses [6].

1.5.4 Tribochemical wear

Tribochemical wear/ chemical wear/ oxidation wear/ corrosive wear induced by friction is influenced mainly by the environment and its active interaction with the materials in contact [7]. Tribochemical wear results from the removal of reaction products/layers formed in situ from the contacting surface [2].

Corrosive wear occurs when the contact surfaces chemically react with the environment and form reaction layers on their surfaces, layers that will be worn off by the mechanical action of the interacting contact surfaces. The mild wear of metals is often thought to be of the corrosive type. Another corrosive type of wear is fretting, which is due to small oscillating motions in contacts. Corrosive wear generates small sometimes flake-like wear particles, which may be hard and abrasive [6].

II. WEAR MODELS AND SIMULATION METHODS

2.1 Introduction

Despite the many efforts, there is still no way of predicting, with confidence or certainty, the tribological performance of a loaded pair of surfaces, whether dry or lubricated, even if all of their physical and chemical properties have been independently established [5].

The wear process can be modelled and simulated, with some restrictions. If the operating wear process, or how to model the wear process, is known, wear can also be simulated and wear can be predicted [6].

In continuous sliding cases, pin-on-disc configuration is used. The pin is held stationary under a normal load while the disc is made to rotate. The loading can be provided by simple dead weight or by spring loading or hydraulic or pneumatic pressure [9].

Pin-on-disc experiments show that the wear is linearly proportional to the sliding distance, at least after a running-in period (Running-in of two fresh and unworn surfaces in contact is a transient phase where friction and wear vary considerably in time. During running-in the surface properties of the components are adjusted. If the initial surface roughness of the rubbing surfaces is correctly
chosen, the running-in changes into the steady-state phase. At this stage, the rubbing surfaces are in general smoother and their wear rate is low and constant [1]).

Most wear models assume linearity, and they often also assume that the wear is directly proportional to the local contact pressure [6]. The most common wear model is named Archard’s Wear Law.

2.2 The Archard wear equation

A common starting point in the analysis of wear is often the Archard (or Rabinowicz) wear equation [5], which asserts that the wear volume \( w \) is directly proportional to the product of the load \( P \) on the contact and the sliding distance \( s \) but inversely proportional to the surface hardness \( H \) of the wearing material [5,10], so that

\[
w = K \frac{P \cdot s}{H}
\]

The dimensionless constant \( K \) is the non-dimensional wear coefficient. The numerical values of \( K \) are always lower than unity, usually very much lower.

When interpreting experimental situations, the hardness of the uppermost layer of material in the contact may not be known with any certainty and, consequently, a rather more useful quantity than the value of \( K \) alone is the ratio \( K/H \); this is known as the dimensional wear coefficient or the specific wear rate and is usually quoted in units of mm\(^3\) N\(^{-1}\) m\(^{-1}\). For a material with hardness of 1 GPa, a non-dimensional wear rate of unity is equivalent to a measured wear rate of 1 mm\(^3\) N\(^{-1}\) m\(^{-1}\). Nevertheless, the specific wear rate serves as a universal parameter for comparison of wear data obtained under different test conditions [2].

There is no simple correlation between friction and wear, although in a qualitative way it is reasonable to expect situations in which there are higher frictional forces to be also those involving relatively high wear, it is quite possible for material combinations to produce very similar frictional forces but very different wear behaviour [5]. Very often high friction and high wear coincide. However, a tribosystem can experience low friction but high wear rate or vice versa, high friction combined with a low wear rate [2].

2.3 Wear maps

Lim and Ashby (1987) [11] have suggested that the various regimes of mechanical and corrosive wear for any particular pair of rubbing materials could be shown on a single wear map plotted on axes of normalised pressure and sliding velocity. In principle the map can be divided into areas corresponding to different wear regimes, with boundaries of sliding speed and contact pressure beyond which a purely mechanical view of wear would be grossly in error, owing to the effects of oxidation. They explored potential of Wear-Mechanism Diagrams. They constructed diagrams which show the rate and the regime of dominance of each of a number of mechanisms of dry wear (delamination, mild and severe oxidation, melting, seizure, etc.) empirically (that is, from experimental data alone) and by modelling (by theoretical analysis calibrated to experiment). They applied this method to steels, and has wider application as a way of classifying and ordering wear data, and of showing the relationships between competing wear mechanisms.

Childs (1988) [8] has criticised this approach on two grounds:

1. It takes no account of differences of surface slope or surface shear strength,
2. It is only of the same practical use as quoting a wear coefficient.

Although plotting of such maps for a wide range of environmental conditions would require the analysis of enormous data, yet they offer the possibility of condensing such data into understandable form.

Williams (1999) [5] identified some factors influencing dry wear rates, which are:

. Normal load
. Relative sliding speed
Geometry (both macroscopic and local or topographic)  
Initial temperature  
Local environment, and  
The thermal, mechanical and chemical properties of the materials involved

The operating point of the design can be located in a map whose coordinates are chosen from the above list and which is split into various territories each associated with some dominant mechanism of degradation [5]. Identifying the operating point of a sliding contact in an appropriate wear map can assist in establishing the possible or likely modes of surface damage and how close the operating conditions are to any transition between mild and severe regimes of wear.

III. BRIEF OVERVIEW OF LITERATURE

Williams (1999) [5] illustrated the difficulties in modelling the wear by looking at the models available for two particular classes of wear involving metallic materials—severe abrasive wear, when surface life is likely to be short, and lubricated mild wear when very much longer component histories can be anticipated. He reported that wear in conditions of sliding contact can vary over many orders of magnitude and there is no universal mechanism of wear and no simple correlation between rates of wear or surface degradation and values of friction coefficient.

Williams (2005) [12] suggested that each of the various processes by which material can be lost from a surface in service leaves its fingerprint both in the topography of the worn surface and in the size, shape and number of the particles which make up the wear debris. To use debris examination as a diagnostic aid in assessing the health of operating plant, which may contain many tribological contacts, requires not only careful and standardised procedures for debris extraction and observation but also an appreciation of the mechanisms by which wear occurs and the regimes in which each of the contacts of interest operates when displayed on an appropriate operational map.

Bressan et al. (2008) [13] investigated the effect on the wear resistance of AISI 630 (UNS S17400) or 17-4 PH stainless steel hardened by precipitation hardening or aging at various hardness levels. They performed the wear tests by sliding and/or abrasion in a pin-on-disc tribometer whose pins had three different hardness levels (43, 37 and 33 HRC) obtained by varying the precipitation hardening treatment. The counterface discs were machined from the same steel composition and aged to the hardness of 43 HRC. The steels wear resistances were evaluated, using sliding velocity of 0.6 m/s, normal load of 30N, total sliding distance of 2400m and controlled room temperature and humidity of 27˚C and 60%, respectively. From the analysis of plotted graphs of cumulative lost volume versus sliding distance, Bressan et al. observed the different wear rates as function of the heat treatment and hardness. Due to the pins of different hardness, the wear resistance varied substantially. The wear mechanisms were also investigated through scanning electron microscopy observations of the worn surfaces of the pins. Bressan et al. asserted that the decrease in the pin hardness yields to lower pin wear resistance. The disc wear was more severe as the difference in hardness between pin and disc increased. Bressan et al. presented a list of mean wear resistance, establishing the best heat treatment that minimizes the wear in this material for sliding wear applications. For the investigated range of heat treatment and hardness, the 17-4 PH steel pins with hardness of 43 HRC showed the best wear resistance and the pin with 33 HRC the worst wear resistance.

El-Sayed et al. (1995) [14] presented a study of the tribological properties of two locally developed polymeric composite materials for bearing applications. They used unidirectional reinforcements by linen and jute fibres, each in turn, in unsaturated polyester resin. They carried out friction and wear tests, in dry conditions, on a pin-on-disc machine. The experimental results, backed by scanning electron microscope examination, revealed that the reinforcement volume fraction as well as orientation has considerable effect on the friction and wear of polyester composites. An increase of fibre volume fraction to 33% increased the coefficient of friction of the tested material by about 14% and decreased its wear rate by about 95% at both low and high values of pressure velocity product (PV limit) when the fibres were oriented normal to the specimen surface. The same increase
in volume fraction of the fibres when oriented in the longitudinal and transverse directions resulted in almost the same increase in the coefficient of friction (16%) while the wear rate decreased only by 65% at low PV value. For the same orientations at high PV value, the results showed no significant effect on the coefficient of friction while the wear rate decreased by 72%.

Yang (2004) [15] carried out pin-on-disc wear tests of tungsten carbide inserts against hot-work tool steel disc, with loads of 40 and 50 kgf, speeds of 100 and 130 m/min; and temperatures of 25, 200, 400 and 600 °C. He used two types of insert (pin) settings. With the first type, the insert was set in full contact with the disc throughout the whole testing cycle. In the second type, the insert was set with an initial angle with the disc at the beginning of the wear test, but would have a full contact at the end of the testing cycle. He found that, with the same testing parameters, the wear coefficient values of the inserts with an initial angular setting were significantly lower than those obtained with inserts that maintained a full contact setting with the counter disc throughout the testing cycle. The ratio of these two wear coefficient values, the wear coefficient ratio, was also found to be an important parameter. Lower wear coefficient ratios were generally obtained in the early stage of transient wear as well as with higher testing temperatures.

Zhu et al. (2014) [16] used a high temperature pin-on-disc configuration to simulate the contact established between a high-speed steel (HSS) work roll and a hot strip material in hot rolling, in which the pin represented the HSS roll and the disc represented a strip steel. The pin surfaces were oxidised due to the heat transfer from the disc while they were in contact. This work focused on the contact behaviour of the oxide scale in the roll bite during hot rolling while the testing temperature was close to the rolling temperature, the Hertzian pressure was similar to the contact pressure and the sliding speed was close to those in the roll bite. Associated with the evolution of the coefficient of friction, the morphologies and micro-structures on the surface of pin were characterised by means of SEM, FIB and TEM techniques to study the tribological behaviour of oxide scale in contacts. The results indicated that the wear mechanism of pin surface varies indifferent stages. At the stages I and II, the oxide scale on the pin surface is significantly deformed. At the stage III, which the coefficient of friction is stable, the wear mechanism is a mixture of adhesion, abrasion and oxidation. The oxide transfer from the mild carbon steel disc to HSS pin significantly contributed to the scale formed on the HSS pin surface.

Stack and Chi (2003) [17] studied the sliding wear–corrosion behaviour of steels in a pin-on-disc apparatus in aqueous conditions. The effects of applied load and velocity were evaluated at various electrochemical potentials in carbonate/bicarbonate solution (buffered pH 9.8). They analysed the results using weight loss and scanning electron microscopy techniques. They identified wear mechanisms in the various environments and proposed a method of identifying the wear–corrosion transitions, in aqueous conditions. These regimes were superimposed on wear–corrosion maps, where the change in wear–corrosion regime was identified as a function of velocity and electrochemical potential.

Kazushige Kumagai et al (2007) [18] investigated the wear behavior of a forged Co-29Cr-6Mo alloy without any Ni and C added by using a tribosystem consisting of a pin-on-disc type wear testing machine in distilled water containing different dissolved oxygen content. Dissolved oxygen content in the distilled water was controlled by aerating with oxygen or by deaerating with argon. They deduced that the overall wear volume is significantly affected by the dissolved oxygen content in the distilled water surrounding the tribosystem.

Grimanelis and Eyre (2006) [19] used a pin on disc wear testing machine to assess the tribological behaviour of low alloy sintered steel, with and without a plasma nitrocarburizing surface treatment. Dry and oil impregnated sliding were evaluated. A wide range of speed (0.2–4.0 m/s) and load (4–600 N) was investigated. The system's components (pins, discs and wear debris) were characterized by SEM, optical microscopy and XRD to identify the wear regimes and mechanisms. They developed wear maps, based on the generated debris characteristics (composition, shape and size) and identified the regimes of mild, severe and transient wear. The transition from mild to severe wear was related to sharp changes of the wear rate. The transient wear regime, interposed between
the mild and severe wear regimes, was detected for the base sintered steel at the speeds of 0.5 and 1 m/s in dry sliding for the load ranges 240–320 N and 80–100 N respectively. Oil impregnation of the base sintered steel expanded the mild wear regime towards higher loads throughout the whole sliding speed range compared to dry sliding. The presence of lubricant at the sliding system eliminated the appearance of the transient wear regime. For the plasma surface treatment, the transition loads were slightly higher than the base sintered steel, not consistently though. The beneficial attribute of the compound layer was in terms of reduced wear rate ($10^{-6} - 10^{-4}$ mm$^3$/m) for as long as it remained on the surface. The operating life of the plasma treated sintered steel was further prolonged in the presence of lubricant, impregnated in the sintered material.

Lim (1998) [20] has discussed about some proposed maps. He analysed that these maps, which present wear data in a graphical manner, are able to provide a more global picture of how materials in relative motions behave when different sliding conditions are encountered; they also provide the relationships between various dominant mechanisms of wear that are observed to occur under different sliding conditions as well as the anticipated rates of wear. He also presented some directions for future work in wear mapping.

Wilson and Alpas (1997) [21] constructed empirical wear transition maps to delineate the load velocity conditions under which wear transitions occurred in an A356 Al alloy and an A356 Al-20%SiC composite. They performed experiments in dry sliding conditions, using a block-on-ring (SAE 52100) configuration, within a load range of 0.2–400 N and a sliding velocity range of 0.2–5.0 m s$^{-1}$. Both materials displayed transitions from mild to severe wear at specific load and sliding velocity combinations. Within the mild regime, two sub-regimes existed for both materials, namely where mixing/oxidation occurred at low sliding speeds to produce a thermally insulating surface layer, and another at higher speeds where this layer was removed. They reported that in the composite an additional wear transition, i.e. from mild to ultra-mild regime, occurred at low loads and velocities where the wear rates of the composite were at least two orders of magnitude lower than unreinforced A356 Al, due to the load supporting effect of the particles at the contact surfaces. In both materials, the transition from mild to severe wear occurred at conditions where the surface (bulk) temperature exceeded a critical value of approximately 125 °C in the A356 Al and 338 °C for the composite. They summarised the temperature data in the form of surface temperature maps on log load versus log velocity axes. They determined wear mechanisms in each regime using scanning electron microscopy, and energy dispersive spectroscopy techniques that were used to analyse morphologies, microstructures and chemical compositions of worm surfaces and wear debris. They identified the dominant mechanisms in each regime and correlated with wear rate and temperature map data to summarise the effects of reinforcement on wear rates and transitions.

Riahi and Alpas (2003) [22] measured sliding wear resistance of a A30 type grey cast iron against AISI 52100 type steel within a load range of 0.3-50.0 N, and a sliding speed range of 0.2-3.0 m/s using a block-on-ring wear machine. They measured the wear rates and surface temperatures as a function of loading conditions. They constructed a wear map to summarize the measured wear rates and mechanisms that control the wear rates. They identified ultra-mild, mild and severe wear regimes on the map. They found the wear rates $8 \times 10^{-9}$ and $9 \times 10^{-7}$ mm$^3$/m at 0.3 N for 0.2 and 0.5 m/s, respectively in ultra-mild wear regime, in the range of $10^{-5}$ mm$^3$/m at low loading conditions, and $10^{-4}$ mm$^3$/m at high loading conditions in the mild wear regime, and $10^{-1}$ to $3.2 \times 10^{-1}$ mm$^3$/m in the severe wear regime.

Podra and Andersson (1999) [23] proposed a modelling and simulation procedure and used with linear wear law and the Euler integration scheme. They analysed a spherical pin-on-disc unlubricated steel contact both experimentally and with FEM. They used Lim and Ashby wear map to identify the wear mechanism. They revealed that the FEA wear simulation results of a given geometry and loading can be treated on the basis of wear coefficient-sliding distance change equivalence. They reported that the finite element software ANSYS is well suited for the solving of contact problems as well as the wear simulation.
IV. CONCLUSION

Wear is considered one of the main challenges in the twenty-first century for engineers and designers of mechanical systems. There is a need to understand the wear mechanisms and to seek new solutions in the field of materials, lubricants, additives for extending the lifetime of components and enhancing the performance.

Research conducted during the past decades shows that wear can be minimized but not eliminated from systems operation due to a large number of parameters which are influencing the evolution of this phenomenon: load, velocity, geometry, environment, temperature, type of lubrication, thermal, mechanical and chemical properties of the materials involved, surface roughness etc.

Depending on operation conditions, the occurrence of wear leads to a change in the geometry of the components. In time, this will affect the functioning of the components.

Although there are still many gaps in our knowledge of the factors involved in tribological interactions, there is sufficient information available to characterise the commonly encountered wear mechanisms. Many techniques are currently available to modify surfaces to improve their wear characteristics, but these are usually applied after a problem has become apparent in service. These techniques are not usually included in the original design because most engineers do not appreciate the effect of operating conditions on the life of components. The precise role of physical and mechanical properties of metals in wear is little understood. Much effort has been expended in our understanding of bulk properties. Considerably more effort is now required to understand surface properties. Design guides for widely used engineering materials in different conditions of treatment are required under specific wear conditions. Few materials combinations have been examined in the metallurgical detail. This approach should be further extended to produce wear maps with their associated atlas of surface and sub-surface microstructure showing both satisfactory and unsatisfactory wear behaviour.

Some guidance and reconciliation between analytical and computational models and empirical observations can be provided by plotting wear maps for specific materials so that the dominant wear mechanism for particular operating conditions can be established and some indication provided on probable wear performance. A challenge facing the research community is the production of a sound theoretical framework to underpin such design aids. However, because of the variety and complexity of the surface conditions it is not straightforward to relate tribological performance to more easily established material parameters.

When material is lost from a loaded surface either entirely or principally through some form of mechanical interaction the concentration, size and shape of the debris particles carry important information about the state of surfaces from which they were generated and thus, by implication, the potential life of the contact and of the equipment of which this forms a part. The full exploitation of this information and the ability to be able to predict quantitatively the future performance or life requires an understanding of the sources and mechanisms of generation of the extracted and sampled particulate debris. In many cases, it is instructive to display the running conditions of a given contact on some form of operational or wear map. This both enables the implications for wear of changes in design, material or operating parameters to be assessed and allows sensible correlations to be made between laboratory-based experimental investigations and observations in the field.

It is clear that future wear equations cannot be synthesized from 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 some that seem to be totally impractical at this time may eventually be the basis for future useful equations. Wear modeling and equation writing will benefit from a new approach.

As a result of its widespread and pervasive economic consequences wear, the almost inevitable companion of friction has been the subject of much scientific and empirical investigation.
The major growth area for the coming time lies in the role of surface treatments for improving tribological characteristics. Design guides for widely used engineering metals in different conditions of treatment are required under specific wear conditions.

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