Journal of Engineering and Technology Management 62 (2021)

Insights into Wear Mechanisms in Tribosystems

Geeteshwar S. Varshney[1]

[1]Research Scholar, M.B.M. Engineering College, Jai Narain Vyas University, Jodhpur, India (Lecturer, Department of Technical Education, Rajasthan).

Abstract

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. Understanding of wear mechanisms is very important in order to design materials which are suitable for wear reduction. Adhesive wear is the wear by transference of material from one surface to another during relative motion, due to a process of solid-phase welding. Delamination wear is a wear process in which thin layers of material are removed from the wear surface. Abrasive wear is the result of cutting or ploughing grooves by a hard material into a softer material. Researches on the wear of materials in contact having relative motion, have brought new understanding and advanced major concepts of tribology. The availability of new testing instruments have made possible the comprehensive 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 (SEM) is one of the most useful tool for surface analysis in tribology. Many techniques currently available to study wear characteristics of material pairs are SEM analysis, wear mapping and wear modelling using ANN,.

Keywords- Tribology, Wear mechanism, Wear models, Wear equations, Adhesive Wear, Abrasive wear.

1.INTRODUCTION

1.1 Tribology

Tribology is the science 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].

A tribosystem consists of two bodies in contact, a lubricant in between them and environment. In a tribosystem, operating conditions, such as friction, 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.

1.2 Contact 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 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 frictional contact area or the degree of contact. 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. 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:

$$\mu = \frac{F}{N} \qquad \text{...(Eq. 1)}$$

where μ 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) [2,3]:

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].

2. WEAR MECHANISMS

2.1 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. Wear 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 to compute wear rates [4].

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 1970s, wear research increased significantly in response to a technological demand for new materials with longer lifetime 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].

Study of wear is one of the main challenges for researchers in the present time. The study of wear is essential for understanding the wear mechanisms and seeking new solutions in the field of materials, lubricants, additives for extending the lifetime of components and enhancing the performance.

Simulation studies and actual component testing can be a way to select materials for a specific application. Actual component testing can be time-consuming, difficult, expensive and thus, it cannot be applied everywhere. Due to massive amount of possible material combinations and rising innovations in upcoming materials, proper material selection for wear resistance is difficult.

It is difficult to describe wear in some certain terms because wear depends on many variables. Wear is a system-derived property of a material pair not an intrinsic property. A wear system have the following mechanical properties of the two same or different materials in relative motion [1]:

(i) Material composition (ii) Microstructure (iii) Chemical phases (iv) Surface preparation process (v) Surface roughness (vi) Contact geometry (vii) Motion and speed (viii) Relative velocity (ix) Load (x) Alignment (xi)Vibration (xii) Temperature (xiii) Contact pressure (xiv) Mechanical design of the wear tester (xv) Lubrication method (xvi) Lubricant chemistry (xvii) Environmental gases etc.

2.2 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 [4]. 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 [4]. Engineers try to design for mild wear condition, which can be obtained by creating contact surfaces of appropriate form and topography. Selecting suitable materials and lubrication is necessary in order to obtain mild wear conditions. However, in order to get mild wear, the contacts are hardened and lubricated in some way. Lubrication will often reduce wear, and give low friction. Mild wear results in smooth surfaces. Changing the operating conditions for any pair of materials at some stage may lead to a comparatively sudden jump in the wear rate and severe wear may occur. Severe wear produces rough or scored surfaces. Severe wear can be catastrophic which always is unacceptable. For example, severe wear may be found at the rail edges in curves on railways.

However, Barwell [in 6] 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.

The scanning electron microscope and the atomic force microscope have provided fascinating insights and detailed information on surface structure. For identifying the dominant wear mechanism, worn surfaces of test samples should be examined with scanning electron microscope (SEM). The scanning electron microscope (SEM) is one of the most useful tool for surface analysis in tribology.

2.2.1 Adhesive wear

Adhesive wear is most common form of wear in mating steel components. Adhesive wear is the wear by transference of material from one surface to another during relative motion, due to a process of solid-phase welding.

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 separation never occurs spontaneously, but by propagation of a crack and is accompanied with deformation and energy loss. The force needed to separate the two solids depends on density of bonds, geometry of samples and velocity at which separation occurs.

If the surfaces are rough or if they are not clean, adhesion is generally not strong. If a liquid which wets the surfaces is introduced, it increases adhesion.

The adhesive wear is influenced by the following parameters characterizing the bodies in contact [6]:

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

Adhesive wear occurs due to adhesive interactions between rubbing surfaces so that the surface oxide film on the asperities is broken, causing direct contact between the two metals. When the adhesive forces of the two metals exceed the strength of either metal, adhesion and subsequently adhesive wear occurs. It can also be referred as scuffing, scoring, seizure and galling due to the appearance of the worn surfaces. Adhesive wear is associated with both mild and severe wear. In literature, two types of adhesive wear mechanisms are reported:

(a) Galling

It is a form of wear caused by adhesion between sliding surfaces. At high stresses, much stronger bond is formed over a greater contact area that results into gross surface damage, and the equipment may even seize. This is referred as galling and it may take place after a few cycles of movement between the mating surfaces. When a material galls, some of it is pulled with the contacting surface, especially if there is a large amount of force compressing the surfaces together. Galling is caused by a combination of friction and adhesion between the surfaces, followed by slipping and tearing of crystal structure beneath the surface. This will generally leave some material stuck or even friction welded to the adjacent surface, whereas the galled material may appear gouged with balled-up or torn lumps of material stuck to its surface.

Galling is most commonly found in metal surfaces that are in sliding contact with each other. It is especially common where there is inadequate lubrication between the surfaces. However, certain metals will generally be more prone to galling, due to the atomic structure of their crystals. For example, aluminium is a metal that will gall very easily, whereas annealed (softened) steel is slightly more resistant to galling. Steel that is fully hardened is very resistant to galling.

Galling resistance is related to the shear strength and hardness. Aluminium bronzes have high values of shear strength and hardness.

(b) Delamination wear

Delamination wear is a wear process in which thin layers of material are removed from the wear surface. When a hard rough slider moves over another hard rough surface the sliding action takes place at the top of the contacting asperities. These asperities mainly deform plastically, although the overall contact stress may be less than the yield stress of the contacting materials, because the local stresses at the small asperity areas are much higher. High contact stresses can generate dislocations, pile-up of dislocations, and crack nucleation at very near the surface. When these cracks and voids join together, loose particles can form because the strength of the sub-surface layer is less than the shear stress applied at the interface between the slider and the surface. These delamination particles are flake-like.

2.2.2 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 soft sliding surfaces cause one or both of them to be abraded [5].

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.

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 [6].

2.2.3 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 [6]. 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.

2.2.4 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 [6]. 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 sometimes generates small flake-like wear particles, which may be hard and abrasive.

3. WEAR MODELS AND SIMULATION METHODS

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 [4].

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.

In continuous sliding cases, pin-on-disc configuration (Fig. 1) is used. Pin-on-disc is an ASTM standard test for studying the wear of material during sliding. The coefficient of friction can also be found by using this test. 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. The benefit of the pin-on-disc configuration is that wear can be studied under steady conditions of speed and load.

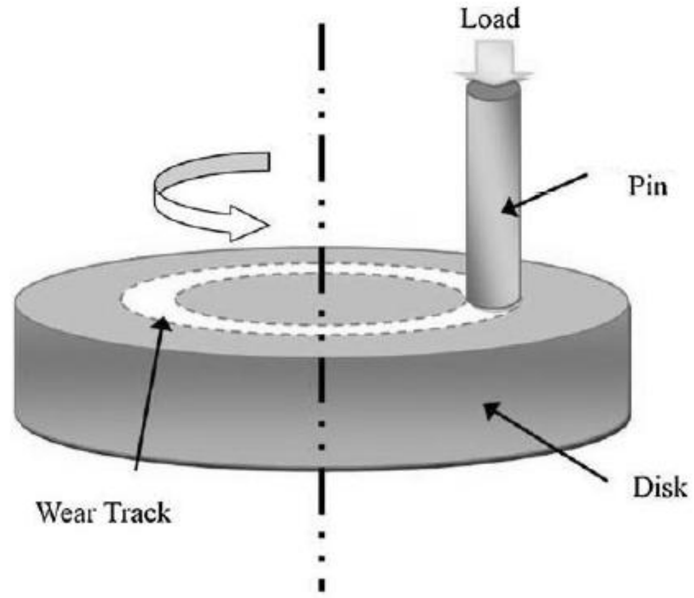

Fig. 1.Pin-on-disc test

Pin-on-disc experiments show that the wear is linearly proportional to the sliding distance [3], at least after a running-in period that is in steady state. 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 phase the surface properties of the components are adjusted. If the initial surface roughness of the rubbing surfaces is correctly selected, the running-in phase changes into the steady-state phase. At this stage, the rubbing surfaces are in general smoother and their wear rate is low and constant.

The pin and the disc should be weighed in an electronic balance with resolution 0.1mg (0.0001 g) to determine its initial mass before testing and mass after testing. Following equation can be used for conversion of mass loss of pin to volume loss of pin:

$$volume\ loss, mm^3 = \frac{mass\ \ loss\ ,g}{density\ ,g/cm^3} \times 1000 \qquad \text{...(Eq. 2)}$$

Sliding speed in m/s can be calculated by using (*πDN/60000*) by knowing wear track diameter 'D'.

All Discs' mass should be recorded before and after each test using electronic weighing machine for disc wear. A precise electronic weighing machine (resolution of 0.1 mg) should be used to weigh the samples. The occurrence of material transfer can be seen by observing the average disc mass loss or gain per unit sliding distance.

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

3.1 The Archard wear equation

A common starting point in the analysis of wear is often the Archard (or Rabinowicz) wear equation [4], 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 (softer material of the material pair) [4,7], so that

$$w = K\frac{P.s}{H} \qquad \text{....(Eq. 3)}$$

Here w is wear volume in mm^3, P is load in N, s is sliding distance in m and H is surface hardness in N/m^2. The dimensionless constant K is the non-dimensional wear coefficient. The numerical values of K are always lower than unity, usually very much lower.

In experimental situations, the hardness of the uppermost layer of material in the contact may not be known with any certainty. Consequently, the ratio *K/H* is more useful quantity than the value of *K* alone. The ratio *K/H* is known as the dimensional wear coefficient or the specific wear rate and is usually expressed in units of $mm^3\ N^{-1}\ m^{-1}$. For a material with hardness of 1 GPa, a non-dimensional wear coefficient (*K*) of unity is equivalent to a measured specific wear rate (or dimensional wear coefficient) of 1 mm^3/N-m [2,4]. Nevertheless, the specific wear rate serves as a universal parameter for comparison of wear data obtained under different test conditions.

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 and relatively high wear. It is also possible for material pairs to produce very similar frictional forces but very different wear behaviour [4]. Cases of coinciding of high friction and high wear is very common. However, a tribosystem can experience low friction but high wear rate or vice versa, high friction with a low wear rate [2].

4. LITERATURE OVERVIEW

Wear is one of the most commonly encountered industrial problem and hence have attracted the attention of many researchers so far. Wear is a complex phenomenon, which depends on a large number of parameters which are: load, velocity, geometry, environment, temperature, type of lubrication, thermal, mechanical and chemical properties of the materials involved, surface roughness etc.

Research conducted during the past decades shows that considerable efforts have been expended on development of various theories of wear, experimental studies on different tribosystem models for wear testing such as pin-on-disc machine, wear mapping, wear modelling and simulation [8]. Various test standards depicting test procedures to standardise the wear testing have also been developed.

The experimental results of wear carried out in laboratory are commonly analyzed by the Archard’s [7] or Rabinowicz’s equation [4] that assess the wear rate and the wear coefficient, relating the cumulative lost volume per sliding unit with the wear resistance through the linear equation:

$$Q(mm^3/m) = \frac{V}{S} = K\frac{F_N}{H} \qquad \text{...(Eq. 4)}$$

where Q is the parameter that measures the wear ratio or “wear rate” (cumulative lost volume V or lost mass per sliding unit S), F_N is the applied normal load, H is the hardness of softer material and K is the wear coefficient, which is non-dimensional and less than unity. In general, the *wear resistance* is defined as $1/K$. Therefore, the *wear coefficient* is given by

$$K = \frac{QH}{F_N} = K_S H \qquad \text{...(Eq. 5)}$$

where K_S is the specific wear coefficient ($K_S = Q/F_N$) unit of which is mm^3/mN. Both coefficients refer to the softer material. In the wear testing on pin-on-disc setup, the softer material is the pin. The cumulative lost volume is obtained by

$$V = \frac{m}{\rho} \quad (m = mass, \rho = density) \qquad \text{...(Eq. 6)}$$

The wear coefficient K is of fundamental importance and provides a valuable parameter of comparison for the severity of the wear process in various tribological systems. Thus, the Archard wear equation provides parameters that describes the severity of wear through the coefficient K, but its value cannot be used to confirm the existence or not of a determined mechanism of material removal. It is necessary to use the optical microscope or the scanning electron microscope to identify the main acting wear mechanisms.

Bressan et al. [9] reformulated the Archard Eq. (2.1) by cosidering the harder material, the material of the disc, by substituting the hardness H by an equivalent hardness H_e ($1/H_e = 1/H_{disc} + 1/H_{pin}$). The disc wear rate increases with the increase in the hardness difference between pin and disc.

Prasad [10] studied sliding wear behaviour of some leaded-tin and aluminium bronzes over a wide range of applied pressures and speeds using a pin-on-disc machine. He monitored wear rate, frictional heating and surface roughness of the samples during the tests. He correlated the wear response of specimens with the features of their wear surfaces, subsurface regions and debris particles, and explained in terms of varying elemental concentrations and specific characteristics of various micro-constituents in terms of thermal stability, cracking and lubricating tendency, and load bearing capability. The study suggested that there is no direct correlation between mechanical properties (like hardness, tensile strength and elongation) and wear response of the samples. Rather the wear behaviour is better understood in terms of micro-structural features. Irrespective of material composition and microstructure there exists a specific set of test conditions (e.g. load and speed) leading to best wear performance wherein the positive effects of load bearing capability, thermal stability and lubricating tendency of various phases predominate over the negative influence of cracking and vice versa. The study also indicated that mere presence of a (solid) lubricating phase (like lead in leaded-tin bronzes) does not always ensure improved wear performance of materials and that appropriate sliding conditions are needed to realise the benefits of the lubricating agent in true sense.

Prasad, 2004 [10] concluded following remarks about sliding wear behaviour of some leaded-tin and aluminium bronzes over a wide range of applied pressures and speeds:-

Wear rate of leaded-tin bronzes decreased with increasing sliding speed while the aluminium bronze showed reverse trend. High wear rates conformed to more severe micro-cracking tendency on and in the regions below the wear surfaces and coarser debris formation. Improved wear performance of the leaded-tin bronzes with increasing sliding speed may result from the suppressed micro-cracking tendency favouring effective smearing of the lubricating phase (lead) leading to lubrication. Deteriorating wear behaviour of the aluminium bronze with speed/pressure may be due to the occurrence of more severe wear conditions leading finally to seizure. Presence of a lubricating phase (like lead in leaded-tin bronzes) does not mean improved sliding wear behaviour. Maintenance of appropriate wear conditions in terms of frictional heating enabling effective smearing of the lubricant phase, such as the lead in leaded-tin bronzes, is equally important in order to achieve the benefits of lubrication. Material removal mechanism mainly comprised crack assisted “chipping off” in case of the leaded-tin bronzes at 0.42 m/s. The wear mechanism changed to wear induced plastic deformation of the subsurface regions followed by the effective formation of heavily deformed transfer layer and lubricating film of lead at higher speed (4.60 m/s); destruction of the layer/film was responsible for material loss at this speed.

Williams [4] described 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. There is no universal mechanism of wear and no simple correlation between rates of wear or surface degradation and values of friction coefficient. Quantitative models are restricted to limited areas of any such map and are material-specific. These models often require material properties or process ‘constants’ which cannot be established other than in a wear test itself and so are self-referential.

Hegadekatte V. et al. [11] discussed the importance and suitability of a wear simulation tool. They proposed that a finite element (FE) post-processor is the optimum choice because in order to predict wear and eventually the life-span of complex mechanical systems, several hundred thousand operating cycles have to be simulated. Hegadekatte V. et al. implemented a wear simulation approach based on Archard’s wear law in an FE post-processor that works in association with a commercial FE package, ABAQUS, for solving the general deformable contact problem. In this tool local wear is computed and then integrated over the sliding distance using the Euler integration scheme. This wear simulation tool works in a loop and performs a series of static FE-simulations with updated surface geometries to get a realistic contact pressure distribution on the contacting surfaces. They demonstrated that this efficient approach can simulate wear on both two-dimensional and three dimensional surface topologies. They computed the wear on both the interacting surfaces using the contact pressure distribution from a two-dimensional or three-dimensional simulation, depending on the case. After every wear step the geometry is re-meshed to correct the deformed mesh due to wear, thus ensuring a fairly uniform mesh for further processing.

5. DISCUSSIONS

5.1 Mechanisms of wear

When two surfaces slide against each other under some load, two forces come into play :

1) The normal load which acts in perpendicular direction to the surfaces in contact. It exerts a compressive force on the materials.

2) The tangential force in the direction of motion which overcomes the following types of resistance:

(i) The friction force which is the product of the load and of the coefficient of friction of the pair of materials in contact.

(ii) The adhesive force which causes the two mating metals to adhere to each other when not separated by an insulating film of a lubricant.

(iii) In some cases, resistance to motion is caused by abrasive material.

These forces develop stresses in the surface and the sub-surface of the mating materials. This may have the following effects [12]:

a) Work-hardening of the softer surface or both surfaces,

b) Producing plastic deformation of the softer of the two materials, particularly when overcoming adhesion,

c) Dislodging particles from the more wear-vulnerable of the two surfaces, when junctions occur.

d) In the presence of abrasive material, grooves are ploughed into the softer material.

Less mass loss during wear process may be attributed to presence of adhesive wear mechanism. Adhesive wear is associated with the development of adhesive junctions at the interface. The strength of these junctions depends on amount of intimate contact between the interacting surfaces in addition to the physical and chemical nature of the interacting surfaces. The amount of intimate contact increases with increase of load. As speed increases, time required to develop adhesive junction decreases which results in poor intimate contact between the contacting surfaces. Hence it can be inferred that tendency to adhesion increases with increase in load but it decreases with increase in speed. Accordingly, the ratio of sliding speed to load (Speed/Load) can indicate about the presence of adhesive wear mechanism in the wear process. With the increase in Speed/Load ratio (either by increasing the speed or by decreasing the load), possibility of adhesive wear may decrease.

With reduced intimate contact between contacting surfaces due to increase in the Speed/Load ratio, wear may not be due to adhesive wear mechanism. A sharp variation in wear with Speed/Load ratio shows dependence of wear on Speed/Load ratio, and thus indicates possibility of presence of adhesive wear mechanism.

The factors which control the wear also control the interfacial temperature rise. The interfacial temperature rise is more related with the wear process rather than frictional force (or coefficient of friction). A sharp variation in temperature rise with Speed/Load ratio in case of dry (unlubricated) sliding condition, shows dependence of inter-face temperature rise on Speed/Load ratio, and thus indicates possibility of presence of adhesive wear mechanism in case of dry (unlubricated) sliding condition.

5.1.1 Adhesive wear

Due to strong adhesive force that develops between mating materials adhesive wear is originated. When the surfaces start to move relative to each other, minute areas of contact between the mating surfaces join together. Adhesion may result in the surfaces being locally bonded together, which is known as a "junction". The coefficient of adhesion is the ratio of the force required to overcome the adhesion to the normally applied load.

When the machine applies a force to break junctions, the resulting stresses in the metals are small, only small fragments of the metals become detached. Reid et al [13] observed no correlation between strain-hardening rate and coefficient of friction or surface damage due to adhesive wear. Subsequently, newly transferred particles collect with the existing transferred layer. Some transferred particles transfer back to the aluminium bronze. The resultant low wear with no debris formation is acceptable in case of moderate adhesive wear, depending on the desired service life. On the other hand, metals which adhere strongly are more liable to generate debris and are therefore more susceptible to galling. An oxide film can reduce or even eliminate adhesion [12].

The beginning of severe adhesive wear coincides with local material transfer to the steel counterface, which increases the roughness of the counterface.

Schumacher [in 12] presented the threshold galling stress (lowest load at which galling damage occurs) of various unlubricated combinations of aluminium bronze and stainless steels and found that

(i) Hardness has no noticeable influence on galling resistance.

(ii) Nickel aluminium bronze has the best galling resistance and nickel aluminium bronze did not gall under test in combination with any of the other alloys and also performed well when self-mated.

(iii) There is no detectable difference in the wear performance of aluminium bronze against martensitic, austenitic or ferritic stainless steels.

In adhesive wear, at the start of test, junctions may form between the asperities of the pair material, and the asperities of the harder material plough the softer material.

Z Shi et al [14] carried out a rolling-sliding unlubricated wear test on a nickel-aluminium bronze against hardened En19 steel. They noticed that two types of wear took place during the wear process:

a) adhesive wear and

b) delamination wear.

Meigh J. H. [12] suggests that abrasive wear must also be added to these two types of wear.

Z Shi et al [14] observed highly deformed areas in the worn samples at some places indicating that both the surface and sub-surface deformation is non-uniform which is due to difference in sub-surface structures and the different level of stresses acting on them. The highly deformed areas consequently form raised areas or "plateaus" of the worn surfaces and are of higher hardness. Due to the higher stresses which act on them, these areas undergo a higher degree of deformation as compared to the rest, and hence, the non-uniformity of deformation is produced.

5.1.2 Delamination wear

Debris generated by the wear process or loose particles originated from the nearby environment may present in a tribological contact. In the very common sliding situation when a hard rough slider moves over a hard rough surface the sliding action takes place at the top of the contacting asperities. These asperities mainly deform plastically, although the overall contact stress may be less than the yield stress of the contacting materials, because the local stresses at the small asperity areas are much higher. High contact stresses can generate dislocations, pile-up of dislocations, and crack nucleation at very near the surface [15] as shown in Fig. 2. The formation of cracks and voids at the sub-surface does not guarantee the formation of wear particles. Because of the small plastic deformation of the surface, a large number of cracks must be nucleated before a loose particle can form. Loose particles can form only when these cracks and voids join together so that the strength of the sub-surface layer is less than the shear stress applied at the interface between the slider and the surface. These cracks and voids may link together by three different mechanisms: growth of voids. crack propagation, and the plastic shear deformation of the metal between the voids [15]. These delamination particles are flake-like and may be some hundred micrometers long. Thus, delamination wear is a wear process in which thin layers of material are removed from the wear surface.

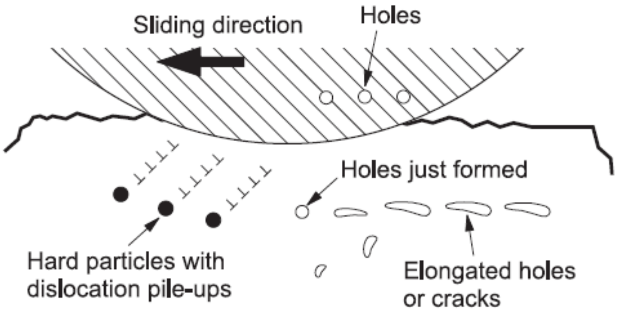

Fig. 2 The schematic representation of delamination process of wear particle formation by joining of voids by the shear deformation of voids [15]

5.1.3 Abrasive wear

Abrasive wear is the result of cutting or ploughing grooves by a hard material into a softer material. The harder material may be one of the rubbing surfaces or hard particles which have found their approach between the mating surfaces. These particles may be ‘foreign’ particles or particles generated from adhesive or delamination wear. Due to the build-up of elastic energy in the transferred layer, some of this layer may detach and form tiny debris [16]. These debris can undergo deformation and work hardening and are therefore responsible to have an abrasive effect on the softer surface and cause severe galling. It may be possible to check this effect by removing the debris. Otherwise, they may lead to rapid deterioration and machine breakdown.

It is recommended to give a finer finish to the harder of the two surfaces to eliminate asperities that can plough into the softer material. The entrance of hard foreign particles should also be prevented.

. The picture that is emerging is that wear is a function of many parameters even for material properties and microstructures. There are no simple rules to predict wear behaviour.

5.1.4 Lubrication

In dry sliding condition, there is no intentional lubricant or moisture is introduced into the wear system. It is also known as unlubricated sliding (sliding without lubricant) condition.

Lubrication is the use of a material to increase the smoothness of movement of one surface over other surface. Decrease in friction between two sliding surfaces is obtained by introducing a material which is capable of reducing the shear stress required to allow the relative motion. Introduced material is known as lubricant and can be solid, liquid, gaseous or any combination of solids, liquids or gases. Solid lubricants strongly adhere to one or both surfaces to be lubricated, and in this way sliding planes are characterized by a low value of shear stress. Liquid lubricants are introduced to the mating surfaces and their action depends on the type of lubrication such as hydrodynamic lubrication, hydrostatic lubrication, elasto-hydrodynamic (EHD) lubrication or boundary lubrication. Gas lubricants (air, N_2, H_2, He etc.) are used in some special cases only.

Besides reducing friction, lubricant may reduce wear or may remove heat from the tribological system (cooling function), and protect the surfaces against environmental attack (preventing oxygen and moisture on the metal surfaces thus protecting from corrosion).

5.1.5 Factors Affecting Wear

Wear is one of the main challenges for researchers of mechanical systems. The degree of wear that occurs is affected by several factors that apply in a given situation. A large number of parameters which influence the evolution of wear are: load, velocity, geometry, environment, temperature, type of lubrication, thermal, mechanical and chemical properties of the materials involved, surface roughness etc. The relation between these factors (or system variables or parameters) is the subject of much research with results that may not always be applicable to all material combinations, particularly the relationship of the wear rate and the load, the speed, the coefficients of friction and adhesion, hardness and tensile and yield strength [13].

(i) **Loading**:- Loading governs the friction and adhesion resistance and as a result the rate of wear of the oxide film. The resistance of metal to severe wear under high load conditions may differ with their wear resistance under low load conditions.

(ii) **Velocity:-** Velocity is one of the factors that affect the erosion of the oxide film although, in some cases, speed has little effect on wear. In other cases it increases the rate of wear and in yet other cases it reduces it. This is because the effect of speed is related to other factors such as lubrication and the temperature it generates by friction.

(iii) **Lubrication:-** The purpose of lubrication is to decrease friction and the tendency to adhesion and to reduce their effects. Effect of lubrication can be observed by comparing variations of wear, coefficient of friction (COF) and temperature rise of interface in both dry (unlubricated) sliding and lubricated sliding conditions at different speeds. There are five types of lubrication:

(a) Hydrodynamic Lubrication: In this type of lubrication, the sliding surfaces are separated by a fluid film having sufficient pressure resulting from the movement of one surface relative to the other. In hydrodynamic lubrication, adhesion is prevented and slight surface distortion occurs [12].

(b) Hydrostatic Lubrication: In this type of lubrication, the lubricant is supplied under sufficient external pressure to separate the opposing surfaces by a fluid film and is able to sustain higher load without contact taking place between the surfaces.

(c) Elasto-Hydrodynamic Lubrication: In this type of lubrication, the pressure between the surfaces are so high and the lubricant film thickness is so thin that elastic deformation of the surfaces may occur. Here, the friction and film thickness between two bodies in relative motion are determined by the elastic deformation of the bodies, in combination with the viscous properties of the lubricant at the prevailing pressure, temperature, and rate of shear.

(d) Boundary Lubrication: In this type of lubrication, an oil or grease, containing a suitable boundary lubricant, separates the surfaces by ‘adsorbed molecular films’. Here, appreciable contact between asperities and formation of junctions may occur. In boundary lubrication, the friction and wear between two surfaces in relative motion are determined by the properties of the surfaces, and by the properties of the lubricant other than bulk viscosity.

(e) Solid-film Lubrication: In this type of lubrication, a solid lubricant is used as a powder or thin film on a surface to provide protection from damage during relative movement by reducing friction and wear. This type of lubrication provides a solid low shear strength film between the surfaces.

It may not always be possible to lubricate in a given wear situation and there are many demanding unlubricated sliding systems in various industries. In other cases, it may be necessary to adapt to a lubricant dictated by circumstances, such as water.

Increase in load and speed can trigger the tribochemical reactions, and the change in the wear behaviour can be better understood in the light of tribochemical mechanisms. The reaction in a water environment also leads to corrosion.

The tribochemical reaction products and wear debris particles provide hydrodynamic lift to reduce the friction in case of water lubricated sliding condition [17].

(iv) **Surface finish:-** Surface finish also affects wear. A well-polished surface finish provides more intimate contact between the surfaces. This results in more interaction between them and may lead to formation of local weld junctions and therefore a greater susceptibility to galling. Lubricants can also sweep away between smooth surfaces. Shot peening of surface helps to retain lubricant.

In case of rough surfaces the asperities will tend to interlock resulting in severe tearing and galling. Most machined finishes fall within an intermediate range of surface finish. For less wear it is recommended to give the harder of the two surfaces a finer finish to eliminate asperities that can plough into the softer material.

(v) **Microstructure and space lattice structure:-** The study carried out by Prasad [10] suggests that there is no direct correlation between mechanical properties (like hardness, tensile strength and elongation) and wear response of the aluminium bronze. Rather the wear behaviour is better understood in terms of microstructural features.

Yuanyuan li and Ngai [18] have carried out wear tests on nickel-aluminium bronzes and found that the microstructure of aluminium bronze alloys, both at its surface and at its sub-surface, determines its wear behaviour. Through adjusting the structure of the alloy, a balance can be achieved between plasticity and hardness. A "soft" structure is more plastic and more prone to adhesion and distortions. therefore it results in a high wear rate. A hard structure is likely to be abrasive and to cause rapid deterioration of at least one of the surfaces in contact. An intermediate structure results in the minimum wear rate which also correspond with the lowest coefficient of friction and the most favourable tensile and yield strength.

The softness or hardness of a phase in a metallurgical structure is a characteristic of its space lattice arrangement. Hexagonal close-packed structures are less ductile than face-centred or body-centred arrangements and generally show lower wear rates and less galling tendencies [Hutchings in 12].

Adhesion also seems to be related to the energy stored in a distorted crystalline structure which is known as its stacking fault energy: the lower this energy, the lower generally is the coefficient of adhesion [13]. Hutchings [in 12] discussed that this is because a low stacking fault energy inhibits dislocation cross-slip and hence favours a high work-hardening rate which in turn results in lower adhesion and friction. Though this correlation does not apply in every case [12].

(vi) **Oxide film:-** It is widely recognised that a stable oxide film, such as copper oxide (Cu_2O), is an essential feature for wear resistance because it reduces or prevents adhesion. The rate at which the oxide film is eroded is a function of load, speed and temperature. It is vital that oxidation should constantly renew this film as it wears in service (it is oxygen in solution in the lubricant which causes oxidation). Indeed, if the load and speed conditions are too severe, then the rate of growth of the copper oxide is less than the rate of surface removal and Cu_2O debris form and cause severe galling or even seizure. This is known as "oxidation wear" [19].

(vii) **Tribological compatibility and adhesion:-** The major cause of ordinary wear is the adhesive wear which is due to the tendency of materials to adhere to one another. Wear is related to the degree of mutual solubility in the solid state of the mating materials. If the mating materials are more soluble in each other, their tendency to adhesion will be higher. Therefore more soluble mating materials are less tribologically compatible. The two materials will be less tribologically compatible in case of higher strain hardening of the softer material of a mating pair. A pair of identical metals are completely mutually soluble and have therefore poor compatibility. The oxide film also affects tribological compatibility. According to Reid et al [13], tribological compatibility also seems to determine whether metal transfer occurs, but tribological compatibility is not related to subsequent surface damage which is more likely is a function of the mechanical properties of the adhered surfaces. Tribological compatibility is the opposite of metallurgical compatibility because more mutually soluble materials are more metallurgical compatible. Reid et al [13] also observed that the copper-aluminium alloy becomes more adhesive than copper-tin alloys if the aluminium content in copper-aluminium alloy is reduced.

(viii) **Coefficient of friction:-** Role of friction in the wear mechanism is still under investigation. As per Hutching I. M. [in 12] there is no general correlation between wear rate and the coefficient of friction. Yuanyuan Li and Ngai [18], have demonstrated that, in the case of aluminium bronze, the effect of changes in microstructure on the coefficient of friction follows the same trend as its effect on the rate of wear. The metallurgical structure and tribological compatibility of mating pairs of materials govern the magnitude of the friction between them with the lowest friction being obtained with most tribologically compatible materials [16,18]. Schumacher [in 12] has reported that some metals experience high friction and low wear and others are the reverse. This inconsistency between friction and wear of different materials may however be accounted for by the fact that any effects that friction may have on wear rate, would not only be dependent on the magnitude of the load and the friction force, but also on the nature of the materials in contact [12].

(ix) **Inter-face temperature:-** Inter-face temperature also influences wear performance of the materials. As per Schumacher [in 12], inter-face temperature may increase either from ambient conditions or from frictional heating due to heavy load and high speed. High temperature has an effect on the oxide film which badly affects wear behaviour. Lubrication reduces both friction and wear rate. Friction can also have an indirect effect on wear by causing inter-face heating. High frictional resistance leads to higher running temperatures, with a consequent effect on wear performance. The speed is also related to friction, and frictional heating in turn may affect the wear performance [12].

(x) **Tensile properties:-** The sub-surface of the mating materials is subjected to a strain gradient when the load and anti-adhesion force together are applied. Mechanical properties of the material resist this strain and govern the amount of deformation that will occur. Yuanyuan Li and Ngai [18] found that, in the case of aluminium bronze, wear rates for different microstructures are inversely proportional to the corresponding yield strength.

Machine component under wear consideration, may also be subjected to bending and other loads, as in the case of gear teeth, cam etc. Therefore a good wear resistant material should also have the good tensile properties. Aluminium bronze has this attractive feature.

(xi) **Elastic property:-** The elastic properties of the softer of two mating materials ensures that deformation can take place under stress without rupture, resulting in delamination and galling.

(xii) **Hardness:-** The harder materials are often found to be the most wear resistant. Aluminium bronze with a hard surface has excellent galling resistance. Earlier, it was thought that wear was inversely proportional to the hardness of the surface being worn away. The relationship between wear and hardness is not clear. Harder material do not imply lower adhesion.

Reid and Schey [13,16] reported that there is no correlation between the coefficient of friction and surface hardness. Yuanyuan Li and Ngai [18] have also concluded the same.

Hardness is an important factor in wear performance up to a certain extent. Higher hardness of the material does not necessarily imply higher wear resistance [18]. It is evident that the combination of one hard and one less-hard (softer) material is an important feature of a successful pair. The softer material is able to set in hard abrasive particles thus minimising damage to the surfaces. The softer material experiences most wear and can be designed to be the cheaper and more easily replaced component. It has been found, in the case of aluminium bronze, that the presence of hard intermetallic particles in a soft constituent of the microstructure is an advantageous feature in resisting wear [18].

Surface hardness can be increased by the work hardening that takes place during sliding or rolling, but higher strain-hardening does not necessarily mean lower friction or lower adhesion [16,18]. Although there is evidence that high-strain-hardening alloys, such as austenitic stainless steel, outwear harder alloys like the precipitation-hardening stainless steel [Schumacher in 12], austenitic stainless steels are notoriously susceptible to galling. The excellent wear performance of aluminium bronze may be due to the fact that, it is a high-strain-hardening alloy. A high working rate in a metal usually gives good resistance to severe wear and galling [Hutchings in 12].

(xiii) **Thermal conductivity:-** The thermal conductivity of at least one of the materials in a mating pair determines the rate at which the heat generated by friction is dissipated and therefore helps to control the inter-face temperature to an acceptable level. High temperature has an effect on the oxide film, mechanical properties etc. which in turn affects wear performance.

(xiv) **Corrosion:-** In the case of corrosive environment, the apparent 'wear' of a metal surface is the result of corrosion followed by mechanical wear of the corrosion product. Corrosion is liable to attack both the surface and sub-surface of an alloy, it is liable to weaken its wear performance. The proportion of wear attributable to corrosion is impossible to assess. Aluminium bronze is a corrosion-resistant material.

5.1.6 The reliability of the wear experiments

It can be argued that the wear experiments using pin-on-disc apparatus, performed according to ASTM G99-95a, actually do not present any real wear situation. However, this standard test method for wear testing with a pin-on-disk apparatus is widely used for determining the wear of materials during sliding. Materials are tested in pairs under nominally non-abrasive conditions. The coefficient of friction may also be determined.

According to ASTM G99-95a, the experiment repeatability is at best when the coefficient of variation of repeated tests lies within 20%. The repeatability of tests on the same material pair depends upon material homogeneity, machine and material interaction, and careful adherence to the specified procedure [20]. Normal variations in the wear test procedure tend to reduce the precision of the test method. Possible causes of variations may be slight variations in material properties such as material homogeneity, hardness, density or thermal expansion rates. Other causes may include presence of wear debris particles, and presence of corrosive environment.

ASTM standard G 115-04 [21] informs that in a wear test, the measured coefficient of friction (COF) is for worn surfaces. These surfaces are separated by wear debris. ASTM standard G 115-04 recommends that coefficient of friction (COF) of worn surfaces should be measured by wear test. ASTM standard G 115-04 also warns that coefficient of friction (COF) of material pair obtained on one type of test set up may be significantly different from coefficient of friction (COF) of the same material pair tested on a different apparatus.

Since the pin-on-disk test method does not attempt to duplicate all the conditions that may be experienced in service (for example; lubrication, load, pressure, contact geometry, removal of wear debris, and presence of corrosive environment), there is no assurance that the test will predict the wear rate of a given material under conditions differing from those in the test [20].

6. CONCLUSIONS AND FUTURE WORK

Wear is one of the main challenges for engineers and designers of mechanical systems. Depending on operation conditions, the occurrence of wear leads to a change in the geometry of the components, which will affect the functioning of the components. Researches on the wear of materials in contact having relative motion, have brought new understanding and advanced major concepts of tribology. The availability of new testing instruments have made possible the comprehensive 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.

Research shows that wear can be minimized but cannot be eliminated from systems operation due to a large number of parameters which are influencing the evolution of this phenomenon. These parameters are: load, velocity, geometry, environment, inter-face temperature, type of lubrication, thermal, mechanical and chemical properties of the materials involved, surface roughness, microstructure and space lattice structure, coefficient of friction, hardness, tensile property etc.

Tribological tests can be carried out by varying load, speed, sliding distance (or time elapsed), lubrication condition (dry or lubrication) on pin-on-disc setup by following test standard described in ASTM (G99-95a) for study of wear behaviour of a material pair in sliding friction taking one material as pin material and other material of disc as counterface material. Various tribological data such as wear, coefficient of friction, temperature etc. obtained from tests can be plotted as function of sliding distance.

The test standards including ASTM (G99-95a) do not address about the lubrication procedure such as flow rate, filtering wear debris particles etc. Therefore, there is a need to develop a test standard which can address about the lubrication procedure on pin-on-disc setup such as flow rate, filtering wear debris particles etc.

ASTM G 115-04 [21] informs that in a wear test, the measured coefficient of friction (COF) is for altered or changed counterfaces. These surfaces are separated by wear debris. Friction characteristics of surfaces may be significantly different from those of a system involving surfaces separated by wear debris. Coefficient of friction (COF) of worn surfaces should be measured by wear test. Literature suggests that coefficient of friction should be determined after a sliding distance of 1000 m.

The wear mechanisms involved in the wear phenomena should also be identified. Although wear is a complex system with dependence on so many variables, there are sufficient literature and information available to characterise the commonly encountered wear mechanisms. Many techniques are currently available to modify surfaces to improve their wear characteristics. For identifying the dominant wear mechanism, worn surfaces of test samples can be examined with scanning electron microscope (SEM). The scanning electron microscope (SEM) is one of the most useful tool for surface analysis in tribology.

Wear mapping is a technique to present wear data in accordance to define the wear system. The operating point of the design can be located in a map whose coordinates are factors affecting wear and this map can be divided into various zones each associated with some dominant mechanism. Identifying the operating point of a sliding contact in the wear map can help in establishing the possible modes of wear and closeness of the operating conditions to any transition between mild and severe wear. 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. An agreement 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 found and wear performance can be predicted.

By using artificial neural network (ANN) technique, an ANN model can be developed, which constitutes one input layer with load, sliding velocity, sliding distance as the input nodes and one output layer with wear, coefficient of friction, temperature as the output nodes (or target nodes). Friction and wear behaviour can be predicted for some new input data by using developed neural network.

REFERENCES

1. Bhushan, B., (2001), Modern Tribology Handbook, Vol. 1 - Principles of Tribology; Vol. 2 - Materials, Coatings, and Industrial Applications, CRC Press, Boca Raton, Florida.
2. Valefi, Mahdiar (2012), Wear and Friction of Self-lubricating CuO-TZP Composites, Ph.D. Thesis, University of Twente, Enschede, the Netherlands,
3. Friction, Lubrication and Wear Technology (1992) (Volume 18) of the ASM Handbook, ASM International.
4. Williams J.A. (1999), Wear modelling: analytical, computational and mapping: a continuum mechanics approach, Wear, Vol. (1–17) pp. 225–229
5. Arnell R. D., Davies P. B., Halling J., Whomes T. L. (1993), Tribology: Principles and Design Applications, Springer-Verlag.
6. Stolarsky T. A. (2000), Tribology in Machine Design, Butterworth-Heinemann, Oxford.
7. Archard J. F. (1953), Contact and Rubbing of Flat Surfaces, Journal of Applied Physics, Vol. 24(8), pp. 981-988.

8. Varshney G. S. and Inkia S., (2017), Wear modelling and wear mapping: A Review, International Journal of Modern Trends in Engineering and Research (IJMTER), Vol. 4,11, pp. 205-214.
9. Bressan J.D., Daros D.P., Sokolowski A., Mesquita R.A., Barbosa C.A. (2008), Influence of hardness on the wear resistance of 17-4 PH stainless steel evaluated by the pin-on-disc testing, Journal of Materials Processing Technology, Vol. 205, pp. 353–359.
10. Prasad B. K. (2004), Sliding wear behaviour of bronzes under varying material composition, microstructure and test conditions, Wear, Vol. 257, pp. 110–123.
11. Hegadekatte V., Huber N and Kraft O. (2005), Finite element based simulation of dry sliding wear, Modelling and Simulation in Materials Science and Engineering, Vol. 13**,** pp. 57–75.
12. H J Meigh C Eng MIMechE (2000), Resistance to Wear of Aluminium Bronzes, CDA Pub 126, 2000, Chapter 10 of 'Cast and Wrought Aluminium Bronzes Properties, Processes and Structure', Copper Development Association.
13. J V Reid and J A Schey – 'Adhesion of Copper Alloys' - *Wear 104 (1985) 1-20.*
14. Shi Z., Sun Y., Bloyce A., Bell T. (1996), Unlubricated rolling-sliding wear mechanisms of complex aluminium bronze against steel, Wear, Vol. 193, pp. 235-241.
15. N P Suh (1973), The delamination theory of wear, Wear, 25, pp. 111-124.
16. V Reid and J A Schey – 'The Effect of Surface Hardness on Friction' - *Wear 118 (1987) 113*.
17. Hsu S.M. and Shen M.C. (2005), Wear Mapping of Materials, In Wear – Materials, Mechanisms and Practice, Edited by G. Stachowiak; John Wiley & Sons, Ltd.
18. Yuanyuan li, T L Ngai (1996), Grain Refinement and Microstructural Effects on Mechanical and Tribological Behaviours of Ti and B Modified Aluminium Bronze, Journal of Materials Science, 31, pp. 5333-5338.
19. J L Sullivan (1986), Boundary lubrication and oxidational wear, J. Physics, D 19, 1999-2011.
20. ASTM, 1995. Designation : G 99-95a (Reapproved 2000); Standard test method for wear testing with a pin-on-disk apparatus.
21. ASTM Standard: Standard Guide for Measuring and Reporting Friction Coefficients (Designation: G 115 – 04).