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ANALYSIS OF WEAR MODELS FOR ADVANCED COATED MATERIALS

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Abstract:

Tribological tests, mathematical modelling and simulations have been conducted over the last few decades to investigate the nature and effects of mechanical wear in coated and uncoated materials. Mathematical models have been developed and in unison with specifically designed empirical tests, the veracity/capability of these models has been investigated. In more recent cases advanced engineering analysis tools, such as FEA and DOE, are used to further compliment and refine experimental techniques.

Studies have focused on the various wear mechanisms: abrasion, adhesion, erosion, corrosion wear, fatigue wear and also on different combinations of these. The intrinsic importance of the material in these studies has lead to a wide range of coated and uncoated materials being used in experimentation and modelling. From analysis, some models are based wholly on established/ classical wear theory while more recent work on wear models have been based on micro and nano scaled scientific approaches.

In practical wear tests, some mathematical models assume certain wear profiles and symmetry for calculating wear volume or mass loss. These assumptions do not account for the very irregular patterns that are the result of most wear mechanisms. Modern instrumentation on the other hand can capture precise profiles and dimensions to produce a more accurate measurement of material loss.

Some authors also use certain parameters such as hardness, fatigue or tensile strength to represent the resistance of a material to wear. Hardness does give an indication of the wear resistance of a material; however studies have demonstrated that the addition of certain alloying elements increases the wear resistance but not the hardness. Therefore hardness alone cannot describe the wear resistance properties of a material.

The objective of this work was to examine a number of models that have been used for analysing wear of materials. It highlights some key details and techniques used by authors to ascertain wear rates and gives examples of modern approaches to wear measurement for coated engineering samples. Figures 1 to 5 show examples of wear on materials and components that are difficult to measure and model in terms of material loss due to their irregular shapes.

Keywords: Tribology, Wear models, Mathematical analysis of wear, FEA, wear Instrumentation

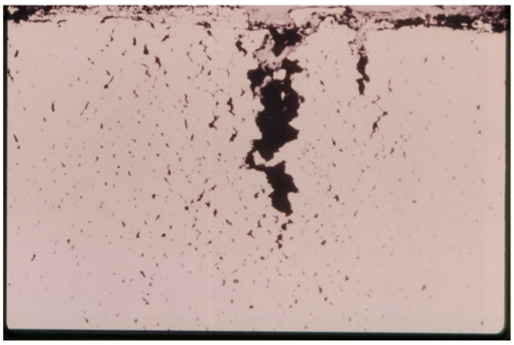

Figure 1 inter-granular corrosion.

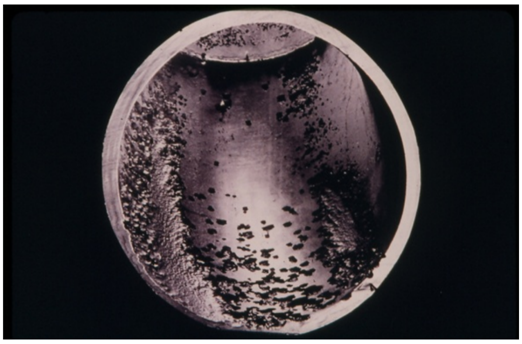

Figure 2 erosion wear in a pipe.

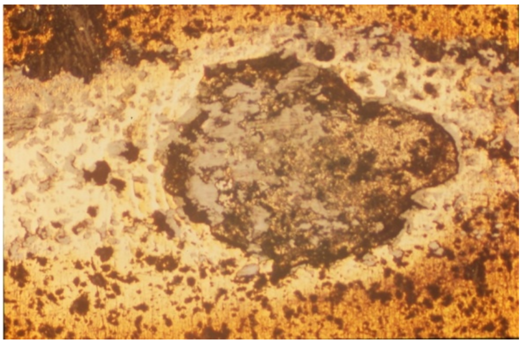

Figure 3 abrasive wear

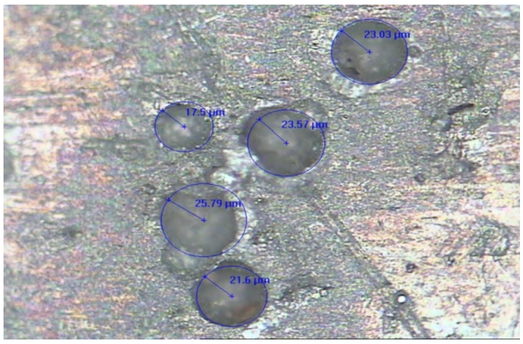

Figure 4 pitting wear.

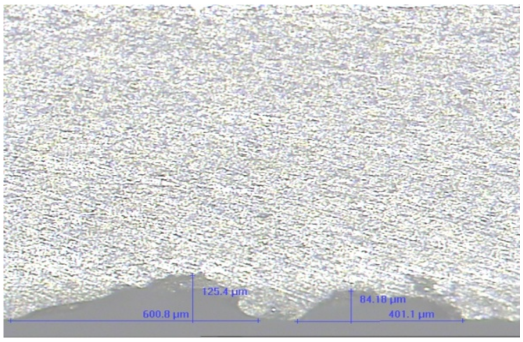

Figure 5 profile of pitting wear.

1. Introduction

Surface Engineering can be defined as the study, characterisation and improvement of a material's surface properties. This surface will be exposed to an external environment and will therefore deal with a different set of constraints/ conditions than the bulk material. Consequently the bulk material can be selected based on structural requirements and the surface of the material can be altered in a number of ways to suit external conditions[1].

This enhancement must be achieved in a cost effective manner without a detrimental effect on the beneficial properties of the bulk material. Common cases where surface treatment is essential are: a cutting tool, punch and dies or dental tools. A classic example of a surface engineering challenge is the gas turbine blade. The turbine environment is highly corrosive and maintained at extreme temperatures; the blade will need to resist these demanding conditions at the surface while also being strong enough, structurally, to transmit a torque to the central shaft of the turbine.

There are three typical methods of improving materials; heat treatment, alloying or surface engineering. Tribology is the science and study of interactions between surfaces in relative motion. Friction, wear and lubrication are fundamental concerns that make up this field [2]. Materials that are in contact have, at the interface, two material surfaces that will have individual characteristics and therefore a different effect on the tribological relationship.

There are a number of inter-related variables that govern how two materials will react in a contact/ Tribological situation. The load applied to bring the materials into contact, the degree of contact between the materials, the presence of a lubricant, sliding speed of the surfaces with reference to each other and the individual material properties. Each variable will have an effect on the system as a whole and it is very difficult to separate out/ differentiate the individual contributions. The material properties of chief concern are the toughness, porosity, hardness and surface roughness. If a surface coating has been applied to a material then the adhesion of the coat to the substrate is important. A major challenge in this field of tribology is found in the accurate measurement of these properties, especially in the case of coated materials. An example of this is the phenomenon of varying hardness with the load applied, or the depth reached in a given material, during an indentation test. This is known as the indentation size effect (ISE)[3] [4] and has led to much discussion and debate.

Wear can be defined as: "The progressive loss of substance from the operating surface of a body as a result of relative motion of the surface with respect to another body"[5]. *Kloss et al*[6] stated that it is a complicated thermal, mechanical and chemical process and is therefore present in an extremely broad range of situations; from the rotating components in a motor to the impeller of a pump to the leading edge of a cutting tool. The loss of material has an obvious effect on the working life of a machine, tool or surface that is exposed to a wear process.

Wear models are used to predict the reaction of a material to a wear situation and to forecast the rate of material removal from the surface of a body. Classical wear theory begins by considering the rate of material removal as a function of the sliding speed, the hardness of the material, the load applied and the probability of a material to produce a wear particle in a given contact situation[7, 8]. There are four main theories that are used as a basis to begin a wear model: a mass balance approach, an energy balance approach, a stress/strain analysis and a contact mechanics approach to determine material behaviour.

Wear can occur in a number of different forms and these processes differ from each other when you consider the bodies that are in contact, the way in which material is removed and in what amount. The processes do not always occur exclusively i.e. several might be present in a given situation. The primary processes are: abrasion, adhesion, erosion, fretting and cavitation. For example abrasion occurs as a physical gouging effect where the harder of the two surfaces will dig into the softer material and subsequently remove material. Fretting operates by a fatigue type action where a build up of incremental strains will lead to material failure. The differences between the wear processes result in possible differences in the failure mechanism of the material e.g. through shearing away of material or through crack initiation and propagation; hence the wear process must be considered when modelling. Research that is focused on a specific application or material in a wearing environment may also include process-specific parameters that will therefore increase the consistency of a model with the application. An example of this would be the inclusion of disparate material regions within a nano-composite coating[9], modelled in an FEA package, or the incorporation of a linked thermo-mechanical simulation to represent a tool wearing situation where heat generation is a very significant factor[10].

Empirical testing is a vital stage in the development of any theoretical model. Through experimentation a proposed model can be verified and problems or inconsistencies are highlighted. It is vital again to account for which wear mechanism is present and to define/ design the test to best represent the situation under examination (WRT bodies interacting, materials, sliding speed, loads etc.).

2. Classical Wear Theory

According to the literature [11], there have been three major stages or trends observed in the development of wear models from the mid to late twentieth century. They are as follows: those based on empirical equations, those founded on a contact mechanics approach and those based on a failure mechanics approach. No general agreement has been achieved, at any level, with regard to wear: its effects, its governing variables and the best method to approach and study this phenomenon. For example during his study *Meng*[11] found that a total of 100 variables have been employed in over 180 models and that no two papers agree on the importance of any one variable in the wear process.

Friction is a very important concept and is intrinsically linked to wear. It remained as a relatively esoteric topic until figures such as Amonton [12, 13] began to study in this field. Equation 1 gives the hypothesis proposed:

$$F_F = \mu F_N \tag{1}$$

Where F_F is the friction force, μ is the coefficient of friction and F_N is the normal load applied. This equation for friction is based on two primary assumptions; firstly the stress distribution is independent of the normal load. Secondly that the load applied is proportional to the real area of contact; if each surface is considered to be composed of a complex topography of asperities then the real area of contact is said to be the common area shared between meeting asperities.

In isolation from Amonton's work, Coulomb [14, 15] also developed the same theory for governing the frictional behaviour of two materials subjected to a normal load. Further to Amonton, Coulomb also proposed that the coefficient of friction was independent of the relative velocity of the bodies.

2.1 Reye (1860) [16]

Reye begins his examination of wear by defining a situation where two bodies are in contact and are in a loaded condition. Figure 6 depicts a rectangular body in contact with a flat surface and a force applied to its top surface. The resultant pressure will be equally opposed from the surface supporting the body. Reye proposed to examine the wear resulting from a tangential stress applied as shown; this would result in an equal force, acting in the opposite direction, at the interface between the two surfaces. He stated that if this tangential stress reached a given value, dependant on the normal pressure and a friction factor *f*, that the body would start to slip. Therefore the equation he derived is very similar to Amonton's friction law:

$$q = fp \tag{2}$$

Where q is the tangential stress and p is the applied pressure. From this point Reye hypothesised that the wear occurring at the material interface, as indicated by the depth of material removed from the surface of the body is proportional to the pressure applied to the material surface

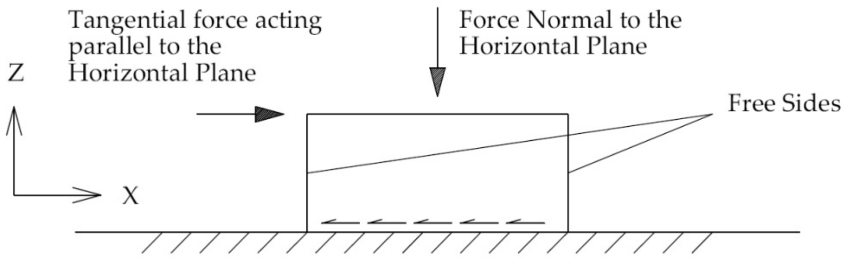

Figure 6. sliding block subjected to a normal and a tangential force (*after Villaggio et al*)

The wear relationship is defined by Equation 3:

$$L_w = K_R p \tag{3}$$

Where L_w is the depth of the wear scar, K_R is a constant of proportionality dependant on the material conditions at the contact boundary and p is the pressure applied over the contact. There have been two major questions that have been raised regarding this theory. The first point of note is the fact that the conditions assumed to be present for the normal load and tangential stress will result in a tangential stress at the free sides of the body, which is not accurate; i.e. a non-uniform distribution of shear stress would actually be the case. Secondly it is assumed that the shear stress is due only to the tangential stress applied at the top surface of the body and it does not take into account the pressure applied. Reye now considered that the volume of material removed form a body was proportional to the energy dissipated into it by the relative motion of the two contacting surfaces[17, 18].

$$V = k_R W \tag{4}$$

Where V is the volume of material removed, K_R is Reye's wear constant and W is the work dissipated into the material. Reye's method was one of the first methods to look at the wear of material from an energy consideration standpoint. Since 1860 there have been a number of investigations that have refined his model or used it as a basis to begin a new model [16, 18, 19].

2.2 *Tabor (1939)[20]*

D. Tabor posited that the actual amount of contact between two bodies is actually much less than the apparent contact area. He has described this phenomenon by saying *"flat surfaces are held apart by small surface irregularities which form bridges"*[20]. His description of surface asperities in contact was substantiated by his empirical investigation into this phenomenon. Tabor and his associate, Bowden, have referenced a number of key developments in the area of contact mechanics. Firstly Hertz'[21] theory on elastic deformation and calculation of the variance of contact area with load was a fundamental beginning. Following on from this Bidwell [22] investigated the conductance between two crossed cylinders. Employing this theoretical basis Tabor *et al*[20] began to investigate the actual area of contact between two bodies. He proposed that since the materials are held apart by the surface asperities an applied load would force greater contact between the bodies and the conductance would therefore be increased. He developed two theoretical equations to predict behaviour of the contact. Using an elastic assumption he stated that the conductivity between the bodies would be dependant on the cubed root of the load applied; similarly, using a plastic assumption, he stated that the conductivity would be dependant on the square root of the load applied.

This hypothesis was tested and verified using a crossed-cylinders apparatus. The findings showed that the actual conductivity (and hence the actual contact area) increased with increasing load and greatest correlation was found with the equation developed using a plastic deformation assumption. Through this work the authors have contributed to the confirmation of Amonton's law of friction. They state: *"The total cross section of the junctions and hence the tangential force required to break them will be directly proportional"*

2.3 *Holm (1946)[23, 24]*

Holm began to consider the process of wear with reference to the relative motion of surface asperities. He envisaged that the individual atoms on opposing asperities were moving towards each other and colliding. His hypothesis stated that the amount of material removed during these atomic interactions was a function of the properties of the materials in contact and the load applied over the contact. This relationship is governed by Equation 5.

$$V = Z\frac{P}{p_{\mathrm{m}}} \tag{5}$$

In the above equation V is the volume of material removed per unit sliding distance, z is the probability of removal of an atom per atomic encounter and would depend on the properties of the materials in contact, P is the load applied and P_m is the flow pressure of a worn surface, which is comparable to the hardness of a material.

2.4 *Archard (1953)[7, 8]*

Archard examined the wear process and decided that there were a number of key considerations that must be included in a wear model. He endeavoured to incorporate these disparate variables into one predictive equation. These considerations are as follows: the wear mechanism (adhesion), the area of contact, the contact pressure, the sliding distance and the material properties[11]. Archard's model is based upon the motion and interaction of opposing asperities on either contacting body. It should be noted that he has referenced Holm in his publications and his work could be thought of as an extension or furthering of Holm's wear equation; they are both centred on a contact mechanics approach, but Archard has decided that the wear regime will depend on a greater number of influences than Holm.

Furthermore he assumed that the deformation occurring was of a plastic type and that the material property of greatest importance was the *"flow pressure"* of the softer metal. Equation 6 is Archard's wear equation.

$$\frac{V}{S} = K \times \frac{P}{p_m} \tag{6}$$

Where V is the volume of material removed (m^3), s is the sliding distance (m), k is the wear coefficient, P is the load applied (N), p_m is the flow pressure of the material under examination. It can be seen that the rate of material removal is directly proportional to the load applied and that independent of the apparent area of contact.

This predictive equation is of great importance and has been used and cited in many empirical and theoretical studies [11, 25-30]. It has been adapted and utilised to model different forms of wear e.g. a fretting wear[30] situation which is a cyclic procedure where incremental stress and strains lead to failure in the material.

There are a number of problems with the assumption that the wear rate is directly proportional to the load, as stated by *Archard*[8]. He had followed on from his pivotal paper in 1953 to document his experimental investigations into wear of metal. He found during these experiments that there were not many situations where this law was substantiated by results obtained. There were two reasons suggested by way of explanation: firstly the surface characteristics of the materials in contact will be changing as a result of material being removed, they will generally become rougher and therefore a change in the friction coefficient by a factor of two or three could result in an alteration of the rate of wear by one or more orders of magnitude. Secondly *Archard* also considered the thermal effects in a wear regime, where surface temperatures is a major factor in the removal of material. He then investigated the heat energy produced at the surface of two connecting bodies that are moving relative to one another[31].

3. Modern Mathematical Wear Models

There are four dominant methodologies employed with regard to modern studies in this field. They are the energy balance, mass balance, stress/ strain analysis and finally a contact mechanics approach. There is no direct connection or agreement between the diverse models and equations to be found in the literature and with reference again to the work of *Meng et al* there is a range of variables and mechanisms in existence that will be seen in only one or two works. There have been a very large number of investigations into very specific applications and wear situations. In some cases authors appear to have arbitrarily chosen not only the variables that are of greatest concern to wear of the contacting materials but also the best manner in which to approach or solve the problem. There has been no formal standardisation as such in this field and this creates difficulties for both researchers and engineers that are trying to combat the effects of wear in its many different forms.

3.1 Fouvry et al (2001)[32]

Fouvry et al began an investigation into the energy absorbed by a hard material subjected to fretting wear. This method centres on a concept whereby the Kinetic energy entered or applied to the tribo-system will be reduced by the dissipative effects of the situation; i.e. a portion of the energy applied will be consumed or used up. There are a number of ways in which this energy can be spent: work done to the contacting materials against friction, to produce heat and to deform the surface asperities (in either an elastic or plastic manner) and hence the production of wear particles. Initially they investigated the suitability of the Archard equation with reference to a situation where the frictional characteristics of the system were not constant. They achieved this by utilising a range of samples with varying porosity in which a solid lubricant was suspended. Thus the coefficient of friction was varied through changes in the material porosity (over which they had control).

These samples were divided into two categories: those with a coefficient of friction (μ) greater than 0.3 and those with a co-efficient of friction less than 0.3. Subsequently a fretting analysis was executed on the samples described above using an apparatus, shown in Figure 1, which oscillates a spherical indenter in a linear pattern over the test material. To investigate Archard's model the product of the normal load and sliding was varied for each cycle (one of each coefficient of friction) of samples to be tested. Once this testing was complete the wear volume resulting was calculating by measurement of the wear scar. A considerable difference was observed between samples that had different coefficients of friction. Archard's wear equation does not incorporate this important criterion and this is, according to Fouvry and the results he produced, a limitation that detracts from the useful potential of his equation and its principal assumptions.

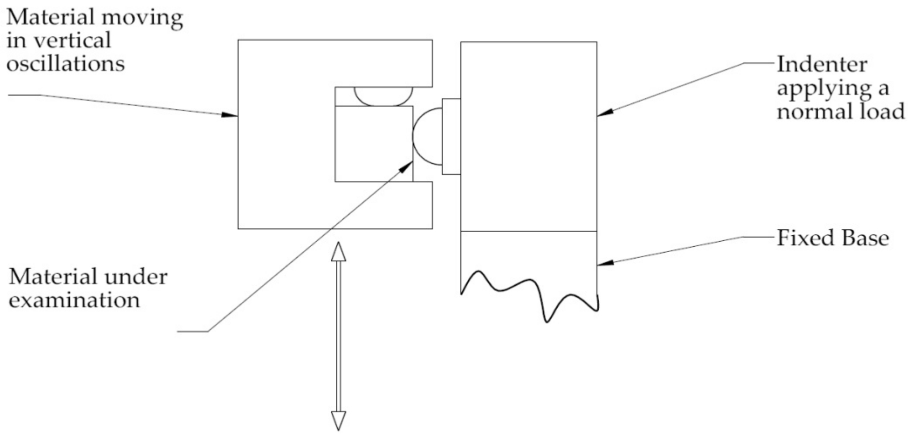

Figure 7 linear fretting apparatus (*after Fouvry et al*).

From here the author considered the energy balance method. He stated *"the wear volume can be compared with the accumulated friction work dissipated through the interface"*. Once again this friction work can contribute to a number of destructive processes e.g. abrasion, heat generation, wear fragment formation and removal etc. To begin the author states that the volume of wear matter produced will be a result of the total energy dissipated into the material, the energy needed to activate wear and will also depend on an energy wear coefficient. This relationship is shown in Equation 7:

$$V = \alpha_V(\Sigma E_D - E_{DA}) \tag{7}$$

Where V is the volume of material removed, α_V is the wear energy coefficient, ΣE_D is the accumulated energy dissipated into the material and E_{DA} is the energy required to activate wear. For the fretting experiment the energy dissipated is equated to the area within the fretting loop, which is a product of the tangential force applied vs. the deflection of the contact plotted on a scatter graph. In addition the energy applied before wear begins is derived from this experiment.

The next stage in the development of this model is the derivation of the energy wear coefficient. To achieve this the author proposes to compare the wear energy components, detailed above, to physical energy components; i.e. binding energy between molecules of constituent material, activation energy required to initiate oxidation and mechanical energy (kinetic, shear). In the following equation the wear energy needed to yield one mole of material from the interface is compared to the yield stress of the materials and the volume produce. This is therefore a comparison of the mechanical elements of energy:

$$E_{\sigma y} = \sigma_y \times V_o \times N \tag{8}$$

Where $E_{\sigma y}$ is the wear energy to yield the material (J/mole), σ_y is the yield strength of the material, V_o is the atomic volume and N is the Avogadro number. Now the energy of wear is considered to be a function of the energy needed to mechanically deform the surface of the material coupled with the activation energy needed to begin oxidation. The energy per mole of material worn is given by equation 9:

$$\varphi_{mol} = C_f(E_{\sigma y} + E_a) \tag{9}$$

Where φ_{mol} is the wear energy required, C_f is a constant related to the contact arrangement, $E_{\sigma y}$ is the mechanical energy to yield the material and E_a is the activation energy of oxidation. This molar energy for wear can now be used to define the energy wear coefficient - by dividing the total volume of material removed by the energy needed per mole of material.

$$\alpha_V = \frac{V}{\varphi_{mol}} = \frac{M}{\rho} \times \frac{1}{C_f(E_{\rho y} + E_a)} \tag{10}$$

Where M is the molar weight and ρ is the density of the material. From this derivation Equation 7 is now a usable description of the wear of material using an energy approach. Through the use of an energy based examination the author has incorporated the friction coefficient of the materials in contact and has therefore eliminated one of the discrepancies of the Archard wear model. Furthermore through the presentation of the activation energy of wear and the use of a wear coefficient the author states that mechanisms of wear can be better understood. In particular the transformation a materials microstructure during the period of "wear activation" can be better studied and understood due to these definitions.

3.2 Savio et al (2008)[33]

Savio et al selected, as a focus for their research, the polishing of glass moulds and the inherent material removal process. This is a very complex application where two primary wear or "damaging" mechanisms will be in operation at any one time. There will be a polishing element due to the polishing tool and an abrasive action due to the slurry used to aid in material removal. In addition there may also be an erosive element but this is not discussed by the author.

This particular application has received a wide range of interest and attention in the literature and a number of key theorems have been recognised[34]. The first hypothesis is that of a chemical action: a film of material is produced due to diffusion of the slurry into the upper levels of the glass and subsequent removal of this layer. The second theory proposes an abrasive type of action whereby a large number of fine cracks are induced into the material due to mechanical contact, the subsequent failure is due to the fracture of asperities. Thirdly a plastic flow concept is introduced where peaks of the material are heated due to friction and then deformed due to the pressure applied to them. Finally a frictional wear hypothesis is a development of the chemical action described whereby the mechanical removal of the film is now attributed to a further chemical interaction between the grains suspended within the slurry and the constituents of the glass.

After study of the pertinent literature in his chosen area the author has decided that the most suitable method for his examination is that of the abrasion deterioration. He proposes to examine the variables of concern to the process, namely: tool deformation, sliding speed, tool dimensions and the initial surface roughness. The wear apparatus of interest consists of a spherical tool which is articulated on three dimensions in a Cartesian co-ordinate system centred on the top of the work piece. As the glass is polished there will be a significant deterioration of the tool and it the apparatus will account for this degradation in order to apply a constant pressure. Thus the contact area will have a circular form that will have a Hertzian [21] type distribution of pressure.

The author now references Reye's approach to the modelling of a wear application i.e. relating the energy dissipated into the material to the volume of debris removed. In this case the formula is written in a differential form to define the rate of volume lost with respect to time. In order to do this the sliding velocity and the pressure are introduced to derive Equation 11:

$$\frac{dV}{A} = K_R p v dt \tag{11}$$

Where dV is the incremental change in volume, A is the contact area, p is the pressure applied over the contact area, v is the sliding velocity and dt is the incremental change in time. This function can now be integrated to determine the volume lost over the total experiment in the following manner.

$$\frac{\Delta V}{A} = \int_0^{\tau} K_R p v dt \tag{12}$$

$$\frac{\Delta V}{A} = K_R v \int_0^{\tau} p dt \tag{13}$$

In Equation 13, the velocity of the tool is assumed constant and so too is the wear coefficient; therefore the pressure will be integrated with respect to the time it is applied over. In the case of equation 12 the tool speed is not assumed constant and nor is the Reye coefficient. The term on the left hand side of this equation is the cumulative frictional work applied. If this term is integrated with respect to the local pressure distribution the frictional work can be described as a function of the experiment parameters, as show below:

$$\int_0^{\tau} K_R p v dt = K_R \frac{4 v_{tr}}{3 v_{av}} E_{eq} \sqrt{R_{eq}} \frac{\Delta^{1.5}}{p_a} \tag{14}$$

Where v_{tr} is the tangential tool velocity, v_{av} is the tool feed rate, E_{eq} is the equivalent modulus of elasticity R_{eq} is the equivalent radius of curvature and p_a is the feed step. Equation 14 is a function of the specific process parameters and as such is a semi-empirical examination of this wear process. It begins on a purely theoretical basis and continues on to integrate process specific and experimentally derived variables to relate the friction work done to the resulting wear parameters. The author has found good correlation with work produced by other authors in the field of polishing wear/ machining[35] with regard to the wear co-efficient.

3.3 Kassman, et al(1991)[25]

This work is of vital importance as it develops a mathematical model for the wear of a coated material and its substrate and then verifies its usefulness through empirical testing. The mechanism of wear that is under investigation is abrasion and the apparatus used to simulate this process is shown in figure 8. The author's goal is to determine the wear behaviour of the coating material and the substrate simultaneously; he states that the difficulties of determining coating properties stem from the fact that most testing performs a composite wear process of the substrate and the coating together. Therefore this methodology is applied with the aim of examining the materials individually.

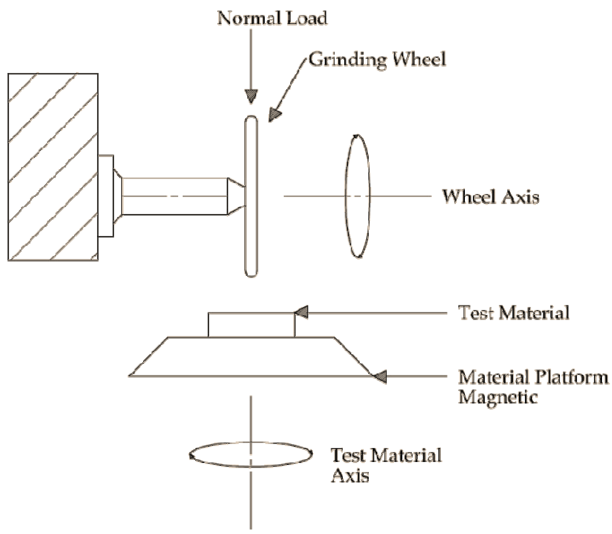

Figure 8 crater grinding apparatus (after Kassman et al).

The *"crater grinding method"* that is proposed is based on a contact mechanics approach and has as its foundation point the wear equation developed by Archard (see equation 6). The derivation of a new model begins by an initial adaptation of this equation. Rather than using the "flow pressure" of the material which is a relatively ambiguous tern, this author uses the load applied and the hardness of the material to formulate:

$$\frac{V}{S} = K\frac{L}{H} \tag{15}$$

Where L is the Load applied and H is the hardness of the material. As the material is essentially a composite there will not be a unified value for the wear coefficient, as each material will have a different affect on the tribo-system. The author introduces a new term to combine the hardness and wear coefficient for each material and this is the wear constant k, given in equation 16.

$$- \tag{16}$$

In addition as the coating is worn and the crater deepens the substrate will have a greater effect on the behaviour of the system; therefore it is proposed to use a weighted mean procedure to ascertain the global wear constant. The rate of debris formation will not be constant either and hence a derivative equation is formed.

$$- \tag{17}$$

Where dV/dS is the rate of change of volume removed with respect to the sliding distance i.e. the wear rate of the material. This equation can be further refined by introducing the volume removed from the coating and the substrate respectively.

$$\frac{dV}{dS} = \frac{d(V_c + V_s)}{ds} = \frac{dV_c}{dS} + \frac{dV_s}{dS} = k_c L_c + k_s L_s \quad (18)$$

Where *Vc* is the volume removed from the coating, *Vs* is the volume removed from the substrate, *kc* is the wear constant of the coating, *ks* is the wear constant of the substrate, *Lc* is the load applied to the coating and *Ls* is the load applied to the substrate. From this point the volume of material removed and the sliding distance travelled is now investigated. The aim of the derivation undertaken is to determine the values of *ks*, *kc* and *t*, where *t* is the depth/ thickness of the coating.

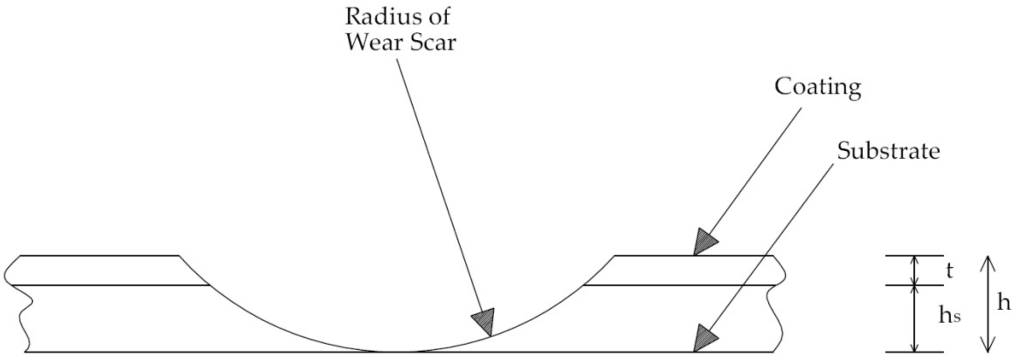

Figure 9 wear scar geometry (*after Kassman et al*)

A wear scar, as shown in figure 9, is used to begin the theoretical undertaking. Through standard geometry the total volume of debris removed from both the coating and the substrate can be found from equation 19 and the volume of material removed from the substrate is given by equation 20

$$V = \frac{\pi}{3} h^2 (3r - h) \quad (19)$$

$$V_s = \frac{\pi}{3} {h_s}^2 (3r - h_s) \quad (20)$$

Where h_s is the depth of the crater in the substrate alone, h is the total depth of the wear scar and r is the radius of the crater. He now separated the differential relationship dV/dS, as it is not possible to obtain a solution from this form, to obtain equation 20 below:

$$\frac{dV}{dh}\frac{dh}{dS} = kL \quad (21)$$

Where dV/dh is the rate of change of volume with respect to crater depth h, and dh/dS is the rate of change of crater depth with respect to the sliding distance. Both of these derivatives can be found: dV/dh can be obtained from equation 19, which will result in an equation with r, h and t as the variables. Similarly dh/dS can be obtained from derivation and manipulation of the equations given here to find a function with r, t, h, k_s and k_c as the parameters. Through the integration of dh/dS, as given in equation 22, the desired theoretical function is obtained and can be used to find the wear constant of both the coating and the substrate independently. In addition there have been two expressions derived dependant on whether the coating has been worn through or not, as can be seen in equation 23.

$$\frac{dh}{dS} = \frac{Lk_c k_s}{\pi}\left(\frac{1}{k_s(2rt - 2ht + t^2) + k_c(2r(h-t) - (h-t)^2)}\right) \quad (22)$$

$$s = \frac{\pi}{L}\begin{cases} \dfrac{rh^2 - \frac{h^3}{3}}{k_c} & when\ h \le t \\ \dfrac{2rt\left(h - \frac{t}{2}\right) - th^2 + t^2 h - t^3/3}{k_c} + \dfrac{r(h-t)^2 - (h-t)^3/3}{k_s} & when\ h > t \end{cases} \quad (23)$$

The apparatus, show in figure 8 is now used to investigate a number of advanced material coatings applied to a substrate of high speed steel (HSS). It is important to note that a datum material of the HSS is used to provide an arbitrary reference point for testing. The experiment was also tested for consistency of results by using a silicon plate. As silicon is a very homogenous material the test is repeated a number of times to see if there is any change for different samples subjected to the same load and sliding distance. It was found that the test will respond to changes of 5% or greater in the wear properties and that there is no appreciable change in wear rate.

The sliding distance of the test was found from the angular velocity of the grinding wheel and its diameter. Now k_s and k_c are found by forming two simultaneous equations from a simplified version of equation 23, hence two h values must be obtained during one experiment. The author states that this method can be used to determine the wear characteristics of very thin coatings while only removing a very small area of material. In addition the characteristics that are primary interest have been found independently as desired. However the assumption that the wear scar will be a perfect segment of a sphere may detract slightly from this approach.

3.4 Fillot et al (2007)[36]

This author begins by firstly referring to Archard and the many other works that have used his law as a basis to begin an investigation into wear. He notes however that the majority of works present in the literature centre on studying a particular application or experiment; therefore they are not suitable as predictive equations for general wear applications. It is proposed in Fillot's paper to approach the concept of wear from a new perspective rather than try and refine an established wear law.

In order to achieve this, the author proposes to approach this phenomenon from a *"global standpoint"* rather than focusing on the particular process of material removal. The author states that Archard's model does not account for the role that wear debris can play on the behaviour of the system and this must be addressed. Godet[36, 37] posited the third body theory to incorporate the particles produced, and contained within the contact area. He defined three important contributions that such a collection would have on the tribo-system: that it would support part of the load applied over the contact, that it will intervene in the contact relationship of the surfaces and that it will participate in *"accommodation velocity"*. It should be noted that in his work, Fillot assumed that the presence of wear particles in the system will act as a dry lubricant, therefore protecting the materials in contact, and not as an exacerbating agent as in the three body abrasion concept.

To formulate an analytical model the author first composes a particular definition of the third body concept stating that wear is a process characterized by three distinct phases: material detachment from the surface of a body, the mass of particles within the contact area and finally the ejection of particulate matter from the system; referring to figure 10 these are *Qs*, *Mi* and *Qw* respectively. As a result the change in mass of particles within the system can be written as a function of the two volume flow rates, as given in equation 24; the author refers to this as the mass equilibrium equation (i.e. it is a mass balance).

$$\frac{dM_i}{dt} = Q_s - Q_w \qquad (24)$$

Subsequently the author defined two relationships that were essential in this wear analysis, these are the connection between Qs and Mi and secondly between Qw and Mi.

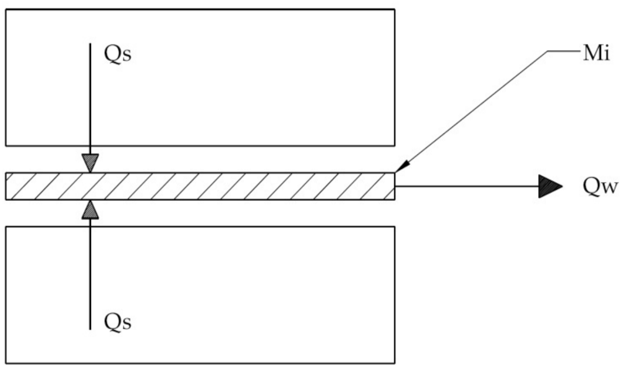

Figure 10 graphical representation of three body concept.
(*after Fillot et al*)

The first relationship (Qs - Mi) is referred to as the source flow activation and represents the particle generation process; as discussed, this was the sole concern of Archard's wear law. The author considers this in three stages. Firstly he states that the normal pressure applied across the contact will be equally shared by the surfaces and the third body. Furthermore he states that the total sliding distance occurring in the system will be composed of the sliding distance of the two surfaces and the sliding distance of the third body, which represents the shear occurring between particles, and uses this definition to arrive at equation 25.

$$dX_{total} = dX_{FB} + dX_{TB} \tag{25}$$

Where dX_{total} is the total sliding distance, dX_{FB} is the sliding distance of the contacting surfaces and dX_{TB} is the sliding distance of Mi. The total velocity of the system is the rate of change of distance with respect to time and therefore can be written as in equation 26.

$$v = \frac{dX_{FB}}{dt} + \frac{dX_{TB}}{dt} \tag{26}$$

Where u is the total velocity of the system. The author now considers the occurrence of shear within the system, stating that, as a preference, shear will occur in the third body rather than at the contacting surfaces as long as it is "easier" to do so. This will cease to be the case when the maximum value of shear stress has been obtained within the third body; hence at τ_{max}. The shear rate can then be expressed as a function of the max shear stress and therefore a function of the velocity within the third body and its thickness as shown in equation 27.

$$\dot{\gamma} = \frac{1}{H_{TB}} \frac{dX_{TB}}{dt} \tag{27}$$

Where γ is the shear rate, H_{TB} is the height of the third body. If the shear rate of the system is assumed to be a constant then the velocity of the third body is proportional to its height. Therefore the mass of the third body can be related to the sliding velocity:

$$\frac{dX_{TB}}{dt} = aMi \tag{28}$$

Where a is a constant of proportionality. No the variable Q_s is considered with respect to the sliding velocity of the bodies in contact. Referring to Archard the volume of material removed from the body is proportional to the sliding distance; hence the rate of change of volume produced (volume flow-rate Qs) will be proportional to the rate of change of sliding distance (i.e. velocity)

$$\frac{dX_{FB}}{dt} = bQ_s \tag{29}$$

$$Q_s = C_s(M_i^{max} - Mi) \tag{30}$$

Where b is a constant of proportionality. Equations 29, 28 and 26 can now be combined to find a relationship between Qs and Mi, as can be seen in equation 30. From this last equation it can be seen that the flow of material from the contact surfaces is proportional to the mass of material already trapped in the contact area. The author does not examine the process of material removal from the surfaces in great detail but he proposes that material removal will occur when the energy present in the system cannot be absorbed by the third body.

The next stage is the development of the *"wear flow activation"* relationship (Qw – Mi). It is stated that the volume of material (per unit time) that will pass through a surface, or area, is found from the double integral of the velocity with respect to the area.

$$Q = \iint_{da} u \, da \tag{31}$$

Where u is the velocity of material passing through the incremental area da. The profile of the velocity as a function of distance from the surfaces is assumed to be analogous to that observed in fluid lubrication, therefore parabolic in profile. As a result the velocity of material at the contacting surfaces will be zero and it will be at a maximum at the centre point of the area da. Using a parabolic equation to describe this relationship between velocity and the thickness of the third body it is possible to perform the double integration in Equation 31 to obtain the following:

$$Q_w = \frac{4}{3}\rho L_x H u_{max} \tag{32}$$

Where ρ is the density of the material, L_x is the length of the contact area in the sliding direction and u_{max} is the maximum velocity of material being removed. Now the flow-rate of material can now be related to the mass of the third body at a particular time and the mass of the third body at the start of the wear regime in the following manner:

$$Q_w = C_w(Mi - Mi^{start}) \quad (33)$$

These two relations can now be solved with respect to a specific duration through the formulation of two sets of ordinary differential equations, one for the initial period of contact and another for the steady state period of wear. To verify the analytical model produced a test was devised in which a drill press was used to apply a pressure and sliding action, thus producing a wear situation. As it is very difficult to measure the actual flow rates of material the authors decided to concentrate on the change in mass produced at a number of locations: the mass of material ejected, the mass of the third body in the contact area and the mass of material removed from one surface. To ensure this was possible one of the materials was chosen to be a degradable surface and one was selected to be a "non-degradable".

The results for this test are as follows: the third body mass rose initially in line with the mass of particles produced then it achieved a steady state and remained at this level for the remainder of the test, the total mass of particles produced and the total mass of particles ejected from the system rose at a constant rate throughout the experiment and therefore the flow-rates, Q_w and Q_s, are also constant.

To conclude the author restates that the aim of this work was not to refine or continue existing wear laws and thinking but to look at this problem from a new angle in order to better describe, predict and understand wear. The author also raises the question surrounding the pin on disc test: i.e. why the wear process is dependant on the orientation in which the apparatus is configured. Therefore the author incorporates the way in which a particle leaves the contact area to try and account for this phenomenon. He suggests that a large amount of time has been spent in defining and investigating the various wear mechanisms but there is a distinct dearth of information on the methods of material expulsion

4. Discussion

There are four main methods of analysis with respect to wear. In this work the papers selected represent three of these four. It should be noted that three of those have referenced, and in some cases used/worked upon, Archard's Law; therefore demonstrating the impact of his work on this field. *Kassman* has used this law as a fundament to begin his study, developing a differential relationship and working to resolve this with reference to a particular geometry produced during testing. Conversely, other authors [32, 36] have stated that the assumptions inherent in Archard's law do not accurately represent the wear process; Fouvry refuted, based on investigation, the assumption that the wear coefficient will not effect the wear process. While on the other hand *Fillot* has questioned the overall approach used by Archard in confining the investigation to a study of the mode of material removal only and not the effect this debris will have on wear performance.

Two of the authors in section 3 have selected an energy balance approach, one utilises a contact mechanics approach and one has used a three body mass balance. An importantly the mass balance approach is significantly different from the other three in that it examines the system from a global point of view i.e. considering the inputs and flow of mass rather than specific processes of material degradation. As a result of this difference in approach the variables used to relate the wear process to the removal of material will also be relatively diverse. The volume removed from a surface is a fundamental variable that is common to all papers; for the contact mechanics and the mass balance the sliding distance is also common but this is where the similarities end. The energy balance approach is concerned with the energy dissipated into the material, however both of the examples above [32, 33] examine this in a different manner: *Savio* begins by developing Reye's wear law whereas *Fouvry* begins an independent investigation into this phenomenon. These two have dissimilar variables even though they employ the same principal model (energy balance). *Fillot's* examination is concerned with the mass and flow rate of material in the system.

Each of the models selected have combined a physical testing procedure with the theoretical aspect of the investigation. However the models begin to differ in the application of these experimental techniques. The ideal case is exemplified by *Fillot et al* whereby the testing apparatus is used to verify the analytical model; *Savio et al* on the other hand first developed a theoretical hypothesis and then began to introduce terms that were specific for the testing procedure and therefore his is a semi-empirical investigation. *Fouvry* began his work by studying Archard's wear law, using a fretting wear test, with respect to the influence the coefficient of friction can have on the wear process; he then used the dissipated energy, recorded during the test to develop his relationship between wear volume and energy dissipated. Finally *Kassman et al* began their mathematical model based solely on the wear scar produced during a very specific testing procedure.

The materials in consideration are fundamental to the behaviour of the tribosystem. With respect to the studies in section 2 there have been a number of different materials used. The most relevant experiment, with regard to the materials employed, is that of *Kassman*. He investigated the behaviour of a two different coated material specimens; the substrate in both cases was HSS and the two coatings were Titanium Nitride and Titanium Carbide. *Savio* investigated glass in a grinding and polishing application, *Fillot* looked at a sintered material (easily deteriorated) and similarly *Fouvry* also used a sintered material in his work.

There is one deficiency to be observed in the examples selected and that is the lack of a sensitivity analysis. In the current literature [11] most authors, when conducting a sensitivity analysis, vary only one parameter at a time to determine the sensitivity of a model to a change in that parameter. It has been suggested that a global approach to sensitivity analysis should be employed using a modern mathematical scheme of weighted variables that interact during the analysis.

In conclusion there is a number of areas in which work is required and a wide range of benefits that can be achieved from a better understanding of wear. The strengths and findings of current models and investigations should be utilized to allow new work to progress and therefore improve our knowledge. It is in the view of this author that a multi disciplinary approach might be very beneficial; this would incorporate a global view to investigate the motion of debris during the process and then a more detailed study of the material removal process to bring an older way of thinking together with a new concept.

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