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TRIBOLOGY AND DEVELOPMENT OF WEAR THEORY: REVIEW AND DISCUSSION

Zamri Yusoff[1], Shamsul Baharin Jamaludin[2]

[1]Mechanical Engineering Department, Polytechnic of Tuanku Syed Sirajuddin, 02600, Arau, Perlis, Malaysia
[2]School of Materials Engineering, University of Malaysia Perlis, 02600 Arau, Perlis, Malaysia.

Email of Corresponding Author: irmazai07@yahoo.com.my

ABSTRACT

In this review, the classical and contemporary wear theories and wear mechanisms are discussed. The development of wear theories are started from adhesive and abrasive to delamination theory, mechanical mixed layer (MML) and self lubrication theory are reviewed based on the previous reports. It was found that the adhesive and abrasive are developed based on quantitative approach whereas the delamination, MML and self lubrication theory are developed based on qualitative approach. Each theory has limitation in order to explain the wear theory comprehensively because of different testing system, composite manufacturing technique, type of reinforcement and volume fraction, size as well as hardness. However, a consensus has been reach from a qualitative point view. Theory of wear debris generation mechanism is the consequence of a combination of subsurface, surface and third body dynamic behaviours. This approach applied in order to explain the wear mechanism usually encountered such as adhesive, two-body abrasive, three-body abrasive, oxidation and delamination. Wear mechanism that occurred during dry siding wear of hybrid composite (multiple reinforcement composite consist of combination of hard and soft reinforcement) is combination of various mechanism and highly complex phenomenon. It well known that wear is nature process that what happen at one time is function of all event that occurred previously. Therefore, based on previous work on dry sliding wear of multiple reinforcement composite, it might be proposed that the wear mechanism involved in integrated wear mechanism.

Key words: abrasive, adhesive, wear theory, delamination, mechanical mixed layer.

INTORDUCTION

The study of tribology has a long history, extending for several centuries before the word itself was coined in 1965.[1] Tribology is the study of friction, lubrication and wear. Professor

Duncan Dawson has remarked that whereas the scientific study of friction dates back some 300 years, and that of lubrication more than century, wear has received similar attention for only 50 years.[2] So, wear entered the scientific arena rather more recently. Essentially, the design and construction of early machines involved large clearances and rather slow speeds of operation, with the result that, provided gross adhesion or excessive friction could be avoided, changes in dimensions of sliding parts due to wear could often be tolerated with little adverse effect on performance. However, development of high-speed internal combustion engine in the early part of twentieth centuries that provided the initial driving force for the study of wear which has grown in importance to the present day. The understanding of wear mechanisms has developed most rapidly only with the widespread use of electron microscopy and instruments methods of microanalysis over the past 30 years.[1] Based on wear studies is so young and so complex, the discrepancies between theories, confusion over nomenclature, and definitions, and inconsistencies between experimental observations is inevitable. However, the foundations of wear studies now seem to be well established. Therefore, this work attempted to review and discuss the development of wear including classical and contemporary wear theories and wear mechanisms based on literature research.

Development of Wear Theory

Historically, the development of wear knowledge and the ability to quantitatively estimate wear made major progress in period 1950-1965.[3] This is the period when the Linear Wear Law (also called the Archard equation) and Khrushov Abrasive Wear law were developed. Wear can be defined as the loss of material that occurs when two surfaces rub against each other.[4] Two common forms of wear are adhesive wear[5-7] and abrasive wear[8-10] . The former occurs when materials of good surface finish and similar hardness are slid against each other and surface forces cause the plucking out and transfer of metallic fragments. The later occurs when abrasive particles or surface protuberances plough and cut fragments from a surface.

Adhesive wear theory

The first theory of adhesive wear was proposed by Archard.[5] This theory was defined wear volume as function of sliding speed, normal load and material hardness. However, this theory ignored the effect of the material's microstructure on wear and was limited to idealised sliding conditions. This theory was based on a mechanism of adhesion at the asperities and the material removal process was related to a cohesive failure of asperities. The processes of crack nucleation and subsequent growth were disregarded. With the assumption that wear particles could be described as hemispherical particles of the same radius as the contact area, Archard developed the following expression for wear rate, W (volume of material worn):

$$W = \frac{KdP}{3H} \qquad (1)$$

Where K = wear coefficient, d = sliding distance, P = applied normal load and H = bulk hardness of material.

Archard concluded that the wear rate was proportional to the applied load (assuming that the average size of the contact areas and the particles were constant) and that the wear rate was independent of the apparent area of contact. The theory predicted that enhance wear resistance was associated with increase in hardness.

Abrasive wear theory

The abrasive wear theory was proposed by Kruschov and Babichev since 1953.[8] They defined that abrasive wear occurs when friction between a metal under stress and a harder body or grain. Abrasive wear may take place during friction of a hard rough steel surface against the surface of a softer, for example, bearing metal. Abrasive wear may be due to various mechanisms which cause surface destruction such as cutting, scratching and single or repeated plastic deformation.[11] According to Hutching[2] mechanisms of abrasive wear can involve both plastic flow and brittle fracture. Under some circumstances plastic flow may occur alone, but both often occur together, even in materials conventionally thought of as ideally brittle. He developed models for abrasive wear separately in two groups of mechanisms; abrasive wear by plastic deformation model and abrasive wear by brittle fracture model. In the first case the hardness of the mating surface is important factor in determining its wear resistance, whereas in the second the fracture toughness is more important, although hardness still plays the role.

Chawla and Chawla[4] stated during abrasive wear, the surface asperities are worn down and the contact surfaces become mated as shown in Fig. 1. This reduces local contact stress because of the increase in contact area. After this initial abrasive wear, the removal of oxidized particles occurs along the surface. This generally a steady state process in as much as it requires re-oxidation of the denuded surface in order to continue removing oxidized particles. The final stage of wear occurs in adhesive mode and occurs if the contact pressure increases to the point of shearing particles. The result of shear is the formation of thin plate-like wear debris sheets. Depending upon applied pressure, the sheets can result in significant material loss.

In studies of two-body abrasive wear, commercial coated abrasive papers have been widely used as abrasive mating surfaces.[12-15] Various relations have been proposed between the variables of the abrasion process, in which the assumption is commonly made that the number of contacting points, for a given mesh size abrasive paper, is independent of load.[9,16,17] Larsen-Badse[15] studied the effect of normal load on the number of contact points in the two-body abrasive wear of metals and found that the number of scratches made on a copper surface by silicon carbide papers was nearly proportional to the applied load. Similar observations were also found by Sin et al.[7] The influence of the nominal grit size of the abrasive particles on the number of contacts was studied by Mulhearn and Samuels[14], Sin et al[7] and Larsen-Badse[15]. They found that the number of contacts per unit nominal area was inversely proportional to the square of the mean abrasive particles.

Furthermore, Spurr[18] studied the surface of aluminium after abrasion by silicon carbide papers. He found that the number of scratches on the abraded specimen surface was proportional to the square root of the applied load rather than directly to the load. Such a relationship was later found also by Miki and Kobayashi.[19] Wang and Hutching[20] reviewed the Spurr[21] reports that the height distribution of the tips of abrasive particles might be normal (Gaussian) but that the abrasive particles which contact the metal surface lie only at the upper end of the normal distribution curve, which may therefore be approximated by a linear distribution over the range of interest. Based on this assumption Spurr[21] developed a semi-empirical relationship between the number of contacts and readily measureable quantities, which states that the number of contacts is proportional to the square root of the ratio of the applied load to the mating surface hardness, and inversely proportional to the diameter of the particles. Full experimental results, however, were not reported by Spurr[21], leaving some doubts about the strength of the experimental evidence for this model.

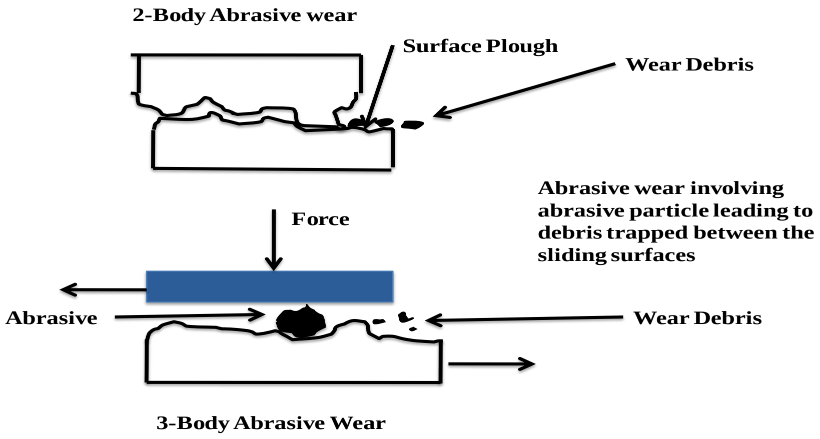

Fig. 1. Schematics diagram of abrasive wear mechanism

Studies of abrasive wear have been done by several researchers on aluminium composite reinforced by silicon carbide.[22-28]

Delamination wear theory

The most widely quoted adhesive wear theory is that of Archard. Archard's adhesion theory has been widely accepted, since the phenomenological relationship between the wear volume, sliding speed, normal load and hardness is consistent with experimentally observed results. However, according to Suh[6], the theory is weak because of completely ignores the physics and physical metallurgy of metal deformation and it does not provide any insight to the wear of metals under different sliding conditions. In 1973, Suh proposed a new theory for wear of metal. He proposed that at low sliding speeds, wear debris formation could be described by a delamination theory. The theory is based on the behaviour of dislocations at the surface, sub-surface crack and void formation, and subsequent joining of cracks by shear deformation of the surface.[6]

Wear processes such as adhesive wear, fretting and fatigue were all related to this same mechanism. The proposed theory predicts qualitatively that the wear particle shape is likely to be thin flake-like sheets and that surface layer can undergo large plastic deformation. Suh[6] stated that wear occurred by the following sequential steps: a) Cyclic plastic deformation of surface layers by normal an tangential loads, b) Crack or void nucleation in the deformed layers at inclusions or second-phase particles, c) Crack growth nearly parallel to the surface, d) Formation of thin, long wear debris particles and their removal by extension of cracks to the surface. The rate-determining mechanism of wear showed dependence on the metallurgical structure. When sub-surface deformation controlled the wear rate, hardness and fracture toughness were both considered to be major influencing factors.

Jahanmir and Suh[29] showed that for microstructures containing hard second-phase particles, if sufficient plastic deformation occurred during sliding wear, crack nucleation was favoured at these particles. In this situation, where inter-particle spacing is an important variable, crack propagation controlled the wear rate. Void formation primarily attributed to plastic flow of the matrix around these hard particles. Void formation occurred very readily around the hard particles but crack propagation occurred very slowly. The depth at which the void nucleation was initiated and the void size tended to increase with increased friction coefficient and applied load.

Studies of delamination wear mechanism on aluminium composite have been done by several researchers.[30-34] For example, Wang et al[33] studied the wear behaviour and microstructural changes of 20vol.%SiC_w/Al composite under dry sliding using pin-on-ring configuration for a range of load (10 – 80N and sliding speed (1.34 – 5.00 m/s) prepared by squeeze casting method followed by extrusion. They found that at heavy load, volume loss is high, the dominating wear mechanisms are adhesion and delamination wear. In SiC whiskers reinforced aluminium composites, the whiskers plays an important role. At depth of about 30µm below the surface, the shear strain is more than 1.3. The large plastic strain in the deformed layers gives rise to void nucleation and subsurface crack initiation and propagation. The subsurface cracks may initiate and propagate along whisker-matrix interfaces and cause the decohasion of whisker-matrix. Crack propagation by SiC-matrix decohesion process has been observed in SiC particulate reinforced aluminium-silicon alloys.[33] The cracks will link to long cracks. With removal of surface material, the cracks become nearer to the surface and the shear strain is increased, this causes the removal of the surface layers by delamination. Delamination wear and the associated nucleation of voids at SiC_p/matrix interface during the dry sliding of MMC pin against a steel counterface also reported by Venkatamaran and Sundarajan.[34]

Mechanical Mixed Layer

It should be noted that the adhesive wear theory[5], abrasive wear theory[8,12] and delamination theory[6] of wear neglect the formation of the tribolayer in their treatment of wear. According to Heilmann et al[35], tribolayer phenomena occurs were common in both dry and lubricated sliding wear processes and developed very early before wear debris loosed. The composition of these layers consisted of an intimate (mechanical) mixture of materials derived from both sliding materials and the loose wear debris had the same structure and composition as the transferred layer. On the worn surface of MMCs a mechanically mixed layer (MML) was present. This layer exhibited hardness approximately 6 times that of the bulk composite.

There have been a number of research works into the formation of mechanically mixed layers and the nature of wear debris in dry sliding systems, especially during Al alloys sliding against ferrous alloys.[36-39] Razavizadeh and Eyre[37] reported that the surface layer on the worn surface of Al-Si alloys was formed by fracture and compaction of Al oxide particles during sliding wear. Iwai et al[40] noted that a tribolayer was formed on an Al 2024 alloy reinforced with SiCw after a sliding distance of only 50m (40N load and sliding speed 0.1 m s^{-1}). Whereas, Zhang and Alpas[32] suggested that the surface layers and debris particles contained an aluminium oxide phase with an amorphous structure, in addition to the original phases of α-Fe and α-Al. In contrast, other researchers[41] found little or no oxide in the wear debris produced in the sliding wear of Al-alloys in an ambient temperature.

Recently, Li and Tandon[40] have studied microstructural characterization of mechanically mixed layer and wear debris of Al-Si alloy and Al-Si/SiCp composite against tool steel under dry sliding conditions. They found that wear debris were mostly detached from the MML and had microstructural features similar to those of the MML.

The debris and MML were comprised of mechanical mixture of ultrafine equiaxed particles, the constituents of which varied depending on the sliding load at the sliding speed used. At low load, the ultrafine structure consisted of original materials, i.e. α-Al solid solution and α-Fe from steel ring. With an increase in the sliding load, the agglomerated debris of nanocrystaline structure was incorporated with Fe-Al (Si) intermetallic compound and aluminium and iron oxides as a result of mechanical alloying and oxidation caused by the large amount of plastic deformation during the sliding process in association with frictional heating.

Deuis et al[41] stated the rationale of researchers in order to explain the formation of MML layer. Initially the MMC material experienced bulk deformation and the shear deformation. With increasing deformation the reinforcement particles at the wearing surface fragmented and the number of voids nucleated at the SiCp/matrix interface increased. When the void density reached a critical value, shear stability, as postulated by Rosenfield[42], was initiated at local subsurface regions. This resulted in the occurrence of turbulence plastic flow, during which time iron and iron oxide debris was mixed in the surface MMC material, resulting in the formation of the MML layer. Venkatamaran and Sundarajan[34] stated that the presence MML layer most probably controlled the wear rate. The formation of wear debris was directly related to delamination wear active within this region.

Self Lubrication Theory

Apart from hard second-phases particle in soft matrix composite, a soft second-phase particles in hard and strong matrix composites are widely used in sliding bearing applications. They possess low coefficient of friction and adapt to diverse operational conditions. Tribological properties of such materials depend in the matrix and the second-phase, as well as the size, shape and concentration of the second-phase particles. The main problem is optimization of the microstructure for the best tribological performance. This task is complicated and requires theoretical analysis. Alexeyev and Jahanmir[45] have attempted to develop self lubrication theory based on quantitative analysis. Slip-line field analysis of plastic deformation is used to analyze the processes of deformation and flow of the soft phase toward the sliding surface. They found a general relationship for deformation and flow of soft phase is obtained. It shows that the properties as well as size and shape of hard matrix and soft second-phase particles control the processes of deformation and flow of the soft phase as shown in Fig. 2.

Solid lubrication is introduced from the solid lubricant cavities (reservoirs) dispersed within the material. These cavities are typically filled with graphite, MoS_2 or soft metal such as Pb, Sn or Ag. The solid lubricant particles deform by the sliding action of the mating surface and are squeezed out toward the surface, forming a soft interfacial film. The presence of this film is believed to be responsible for the observed low friction and reduced wear. When the solid lubricant film is worn away, the resulting increase in friction accentuates plastic deformation of the surface layer and forces more material from second-phase particles toward the surface, thus re-forming the worn film. The beneficial effect of self-lubrication depends on the thickness of the film, the relative plastic properties of the film and the sublayer, and the pressure experienced by the soft film and sublayer[43]. Very few studies have been done on the processes of film formation and destruction.[44,45] The exact mechanism for the adhesion of the film and substrate remain unclear.

In order to understand the tribological behaviour of metal matrix self-lubricating composite, the basic mechanism of the formation of lubricating films must be developed. The early studies of wear behaviour on self-lubricating aluminium composite using graphite as solid lubricant have been done by several researchers.[46-50] However, study on the formation of lubricating film at worn and mating surface are did not discussed thoroughly until Liu et al.[44] He attempted to describe the smearing process of the embedded graphite particles in aluminium 2014 alloy during sliding in great detail based on qualitative analysis by optical microscope. They found that the reduction in friction and wear of the aluminium-graphite composites is result of the embedded graphite particles during sliding, forming a lubricating film on both the tribosurface of the composite and the steel mating surface.

Whereas, Alexeyev and Jahanmir[47] attempted to describe the process of film formation in self-lubricating composites and deformation of the film based on quantitative analysis by the slip-line field method. The results show that the size of second-phase particles in the composite, the relative shear yield limit of the matrix and the soft phase, and the thickness of the film control the tribological performance of these composites. Lin et al[49] also studied the process and tribological behaviour of Al6061/graphite particulate composite. They found that the tribological behaviour of the composite depends on the hardness of the matrix, the rate of release graphite particulates, the structure of the solid lubricating film deposited on the wearing material, and the structure of Al chip clusters.

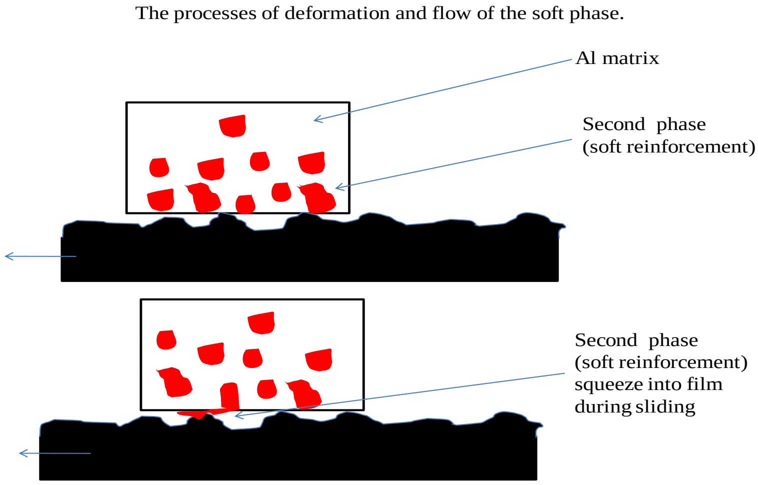

Fig. 2. Schematics diagram of the process of deformation and flow of the soft phase

General discussion

Development of five wear theory might be summarized as shown in Fig. 3. However, in 1995, Sanino and Rack[51] proposed the theory based on debris generation in order to shows the wear mechanism in integrated manner. They stated that wear debris generation mechanism is the consequence of a combination of subsurface, surface and third body dynamic behaviours. This approach applied in order to explain the wear mechanism usually encountered such as adhesive, two-body abrasive, three-body abrasive, oxidation and delamination.

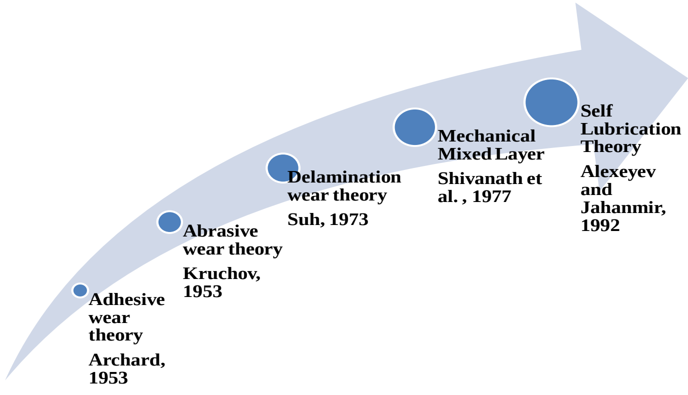

Fig. 3. Development of wear theory

Based on literatures, since year 2000, there are some research focuses on the role of soft reinforcement particle in hybrid composite.[52-61] Aluminium hybrid matrix composite consist of two or more reinforcement added in aluminium matrix. The soft reinforcement likes graphite and carbon fibre, whereas the hard material likes Saffil fibre or SiC particles in hybrid composite. Some researchers have studied the sliding wear behaviour of aluminium hybrid composite found that the hybrid composite showed the best performance in wear resistance. Their result showed more stable tribo-layers on the contact surfaces of the graphitic composites compared to non-graphitic composites However, the hard constituents in the tribo-layers were the scuffing damage that they inflicted on the counterface.

Wear mechanism that occurred during dry siding wear of hybrid composite (multiple reinforcement composite consist of combination of hard and soft reinforcement) is combination of various mechanism and highly complex phenomenon. It well known that wear is nature process that what happen at one time is function of all event that occurred previously. Therefore, based on previous work on dry sliding wear of multiple reinforcement composite, it might be proposed that the wear mechanism involved in integrated wear mechanism as shown in Fig. 4.

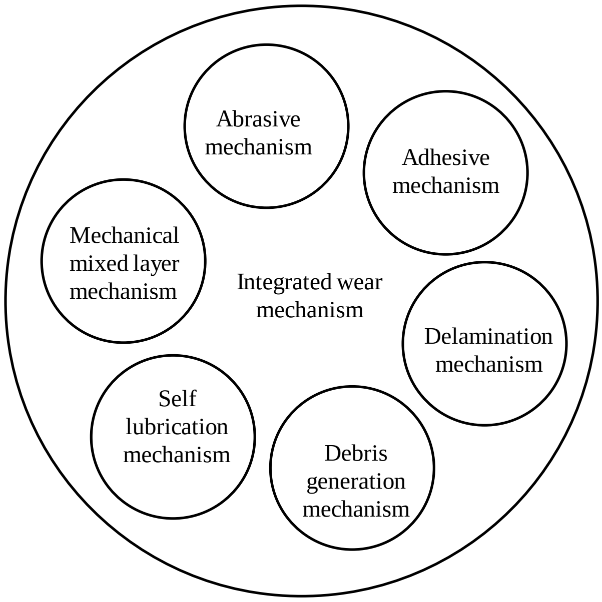

Fig. 4. Integrated concept of wear mechanism occurred during wear process

CONCLUSION

The purpose of this paper was to highlight the development of wear theory since 1950's up to contemporary theory. It can be concluded as follow:

Adhesive wear is influenced by critical parameters such as applied load, speed and environment. Abrasive theory is influenced by contact geometry, matrix and hard reinforcement phase as well as interface characteristics. Delamination theory is influenced by changing of subsurface behavior because of load, speed, fracture toughness as well as creep/fatigue effect. MML theory's influenced by mechanical and chemical reaction during sliding process. Self lubrication theory is influenced by the smearing of soft reinforcement phase on the contact surfaces during sliding process. Wear mechanism that occurred during dry siding wear of hybrid composite (multiple reinforcement composite consist of combination of hard and soft reinforcement) is combination of various mechanism and highly complex phenomenon.

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