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MICROMECHANICAL APPROACH TO WEAR MECHANISMS

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ABSTRACT

Classification of wear process can be done according to different view points. Wear mechanisms should not be mixed with wear types. Study of tribology must incorporate a detailed understanding of the mechanics of contact of solid bodies. In most contact situations, it is found mixture of both elastic plastic deformations. Thus, the loads applied to solids in contact may induce elastic behaviour in the bulk of the solid bodies, localised plastic deformation at asperity tips and affects wear properties of the mechanical system

Key Words: Wear mechanisms, Contact mechanics.

AŞINMA MEKANİZMALARINA MİKROMEKANİK YAKLAŞIM

ÖZET

Aşınma olayının sınıflandırılması, değişik bakış açılarından yapılabilir. Aşınma mekanizmaları, aşınma tipleri ile karıştırılmamalıdır. Triboloji ile ilgili çalışmalar, katı cisimlerin temas mekaniğinin detaylı bilgileri ile desteklenmelidir. Çoğu katı temas durumlarında elastik ve plastik deformasyon beraber bulunur. Böylece, temas halindeki cisme etki eden yük, cismin özünde elastik deformasyona yol açarken, yüzey pürüzlerinin uçlarında da lokal plastik deformayon oluşturur. Bu da mekanik sistemin aşınma özelliklerini etkiler.

Anahtar Kelimeler: Aşınma mekanizmaları, Kontak mekanik.

1. INTRODUCTION

The progressive loss of substance from the surface of solid body by mechanical action is generally called wear. There are also a variety of definitions of wear. In common usage, the term is often ambiguously used to describe both the processes of wear and its results. To avoid this ambiguity, for the process the term "wear process" may be used, and the results of wear may be characterized by terms "appearance of wear" or "wear measuring quantities". The major problem in the study of wear, both as a subject for academic research and its consideration as an engineering problem, is the answer to the question: "how are the worn particles removed". The most common errors in wear control are lack of recognition of the fact that there are many different forms of wear and that each must be considered independently.

2. CLASSIFICATION OF WEAR MECHANISMS

An understanding of wear processes begins with a proper classification. To classify the wear, scientists have followed many ways. Here, there is the most important point not to be mixed, which can be specified as the types of wear (related to motion types, to contact types, to appearance of surface, and to contact elements, etc.) and the mechanisms of wear resulting from the effect of the operating variables (way of particle removal, energy and material interactions). Wear mechanism means the physical and chemical processes occurring during wear. If classification is based on the analogy of the terminology used in the study of the strength of materials, i.e. wear being classified on the basis of the types of tribological action, it is possible to distinguish various "types of wear" according to the tribological action (particularly kinematics) and the system structure. It should be borne in mind, that various wear mechanisms can be involved in every wear process type (Table 1) (DIN 50320, 1979).

Table 1 Classification of Wear Phenomena According to the Type of Tribological Action (DIN 50320, 1979).

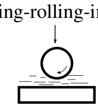
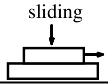
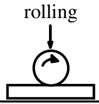
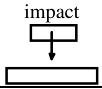
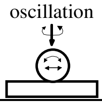
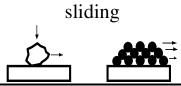
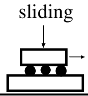
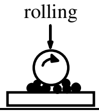
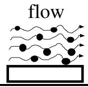
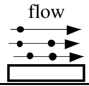
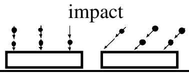
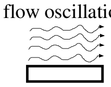
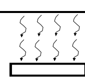
System Structure	Tribological Action (symbols)	Types of Wear	Effective Mechanisms (individual or combined)			
			Adhesion	Abrasion	Surface fatigue	Tribochemical reaction
Solid -Interfacial medium (full fluid film separation) -solid	sliding-rolling-impact 	-			X	X
Solid -solid (with solid friction, boundary mixed lubrication)	sliding 	sliding wear	X	X	X	X
	rolling 	rolling wear	X	X	X	X
	impact 	impact wear	X	X	X	X
	oscillation 	fretting wear	X	X	X	X
Solid -solid and particles	sliding 	sliding abrasion		X		
	sliding 	sliding abrasion (three body wear)		X		
	rolling 	rolling abrasion (three body wear)		X		
Solid -fluid with particles	flow 	particle erosion (erosion wear)		X	X	X
Solid -gas with particles	flow 	fluid erosion (erosion wear)		X	X	X
	impact 	impact particle wear		X	X	X
Solid -fluid	flow oscillation 	material cavitation, cavitation erosion			X	X
	impact 	drop erosion			X	X

Table 2. Wear Processes According to Hammitt (Peterson, 1980).

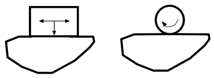
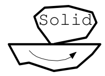
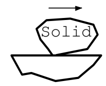
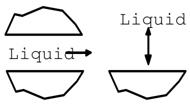
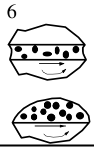
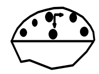
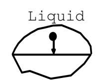
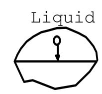
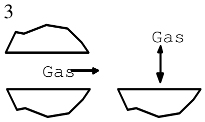
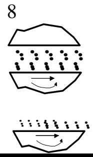
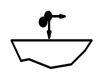
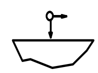
Carrier	Single Phase Wear	Multi Phase Wear					
		Solid Particle		Liquid Particle		Gas Particle	
		Wear surface moving	Carrier and particle moving	Wear surface moving	Carrier and particle moving	Wear surface moving	Carrier and particle moving
Solid	1 	4 	5 	10 -	11 -	16 -	17 -
Liquid	2 	6 	7 	12 -	13 	18 -	19 
Gas	3 	8 	9 	14 -	15 	20 -	21 -

Table 3. Classification Of Mechanism According To Archard (Peterson, 1980).

1. Adhesion and transfer	Materials weld at sliding asperity tips, is transferred to the harder member, possibly grows in subsequent encounters and is eventually removed by fracture, fatigue or corrosion.
2. Corrosion film wear	A film formed by reaction with the environment or the lubricant is removed by sliding.
3. Cutting	A sharp particle or asperity cuts a chip
4. Plastic deformation	A surface is worked plastically. Cracks form, grow, and coalesce forming wear particles.
5. Surface fracture	If nominal stress exceeds the fracture stress of a brittle material, particles can be formed by fracture.
6. Surface reactions	One material dissolves or diffuses into another.
7. Tearing	Elastic material can be torn by a sharp indenter.
8. Melting	High generated temperatures can cause wear by melting.
9. Electrochemical	The difference in potential on the surface due to moving fluid can cause a material to go into solution.
10. Fatigue	The surface is worked elastically. Microcracks form, grow, and coalesce forming wear particles.

Another possible general classification scheme divides wear into two general categories, single phase wear, and multi phase wear proposed by Hammitt (Table 2) (Peterson, 1980). In the table 2, there are some blanks which represent nonwearing cases.

Rabinowicz (1966) and Halling (1978) have stated four main forms of wear (adhesive, abrasive, corrosive and surface fatigue) as well as most researchers. Along with these, that have accepted as wear form specified minor types of wear, such as fretting, erosion and cavitation, etc.

Kislik lists (Peterson, 1980) the following wear mechanisms: mechanical destruction of interlocking asperities, asperity fatigue, failure due to working, flaking of oxide films, molecular interactions and mechanical destruction due to high temperatures.

Another classification is proposed by Archard (1980) as shown in table 3. Further, he has approached wear problems as mild (acceptable) wear and severe wear.

Ludema (1992), has classified the wear processes under three main topics which have subgroups as,

- Wear by particles or fluids
  - -Abrasive wear
  - -Polishing wear
  - -Solid particle erosion
  - -Cavitation erosion
  - -Liquid impingement erosion
  - -Slurry erosion
- Wear by rolling, sliding, or impact
  - -Sliding and adhesive wear
  - -Fretting wear
  - -Rolling contact wear
  - -Impact wear

- Chemically assisted wear
  -Corrosive wear
  -Oxidational wear.

3. SURFACE DAMAGE

Surface damage is defined as topographical or microstructural changes, or both, in a surface layer. Diagnosing surfaces concerning the mechanisms and processes that caused the damage, and relating those mechanisms to geometry, materials properties and other characteristics of tribosystem, can be instrumental in reaching a deeper understanding of tribological components. Surface damage to a tribosystem is most often generated in many consecutive small steps by a number of different mechanisms. In principle, a tribosurface may exhibit damage of single type, but generally the pattern is a combination of two or more types. All types of damage shown in Fig. 1 will in practice influence a surface layer (Hogmark, 1992).

All of these surface damage patterns are main failure way of contacting surfaces, in fact several damage mechanisms have been operating simultaneously. The overlapping mechanisms interact to mutually increase the effects of one another. For example, simultaneous corrosion and wear involve in high temperature erosion.

The effects of certain type of damage and recommended action for reducing the problem vary greatly from case to case. Generally the problems can be divided into the following groups:

- Material losses eventually consume the wear part (excavator teeth)
- Material losses deteriorate the function (by causing cutting edge blunting)
- Disadvantageous topography, structure or composition deteriorates the function (for example, rough topography of forming tools)
- Wear particles deteriorate functions by causing abrasive wear (Hogmark, 1992).

4. CONTACT OF SURFACES

As known, all engineering surfaces are rough. In tribological terms, this is their first important characteristic. Tribology, therefore, involves the mechanics of contact and it is usual to represent surface asperity (protuberance) as a part of sphere. It is concerned with events small but intense in scale. Through the understanding such events, one can interpret the processes of friction and wear. The details of what happens during these contacts will be discussed later.

Further result of asperity contact is the removal of material from the surfaces. The removal of such particles can occur in a number of different ways by mechanisms that have probabilities varying over a very wide range.

Any study of tribology must incorporate a detailed understanding of the mechanics of contact of solid bodies. This requires an understanding of the nature of the associated deformations and the stress induced by any applied loading to bodies of a wide variety of geometric shapes. Deformation of solids induced by any load may be resolved into a normal and a tangential component, and it is generally convenient to consider separately them.

In most contact situations we find a mixture of both elastic plastic deformations. Thus, the loads applied to solids in contact may induce elastic behaviour in the bulk of the solid bodies, localised plastic deformation at asperity tips.

When a sphere is pressed against another sphere or against a flat surface under a light load (N), the deformations are entirely elastic. From the consideration of symmetry, the area of contact will be a circle. The expressions which describe such elastic contacts are the Hertz equations and they may be expressed in the following form (Halling, 1978; Johnson, 1985, Archard, 1980, Czichos, 1992, Winer and Cheng, 1980).

The profile of each surface in the region close to the origin O can be expressed as,

$$z_1 = \left(1/2R_1'\right)x_1^2 + \left(1/2R_1''\right)y_1^2$$

and (1)

$$z_2 = -\left[\left(1/2R_2'\right)x_2^2 + \left(1/2R_2''\right)y_2^2\right]$$

where R'_1 and R''_2 are the principle radii of curvature of the surface at the origin, and the directions of the axes for each body are chosen to

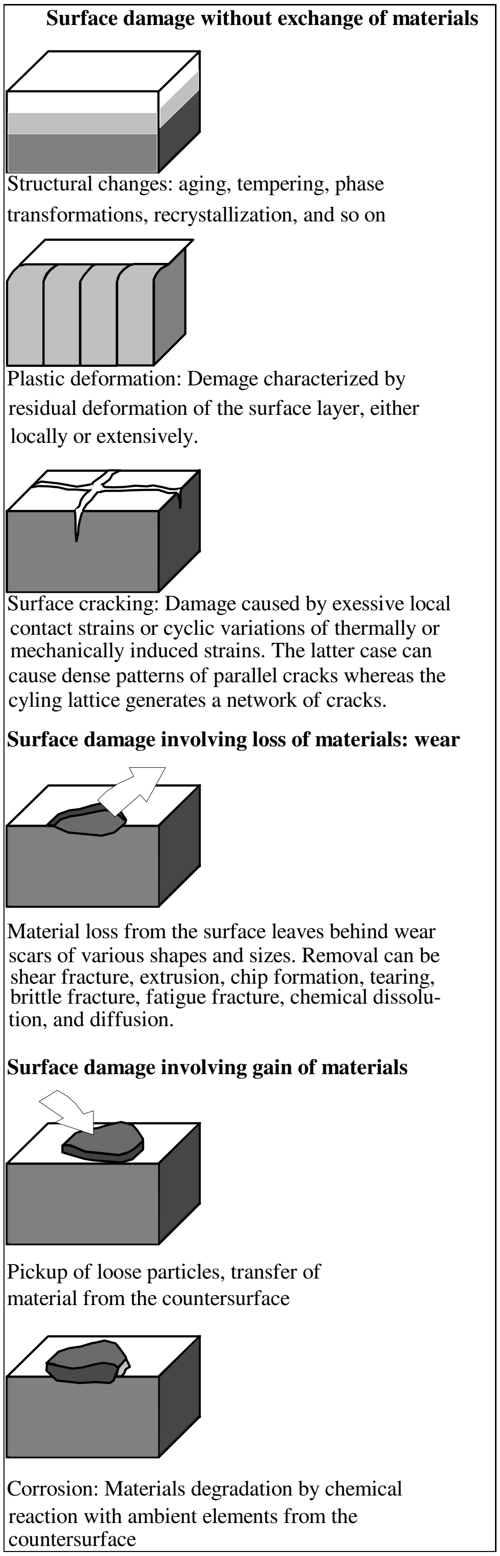


Figure 1 Classification of surface damage

coincide with the principal curvatures of the body. In general, the two sets of axes may be inclined to each other at an arbitrary angle θ, as shown in Fig. 2a. We now transform the coordinates to a common set of axes (x,y) inclined at α to x_1 and β to x_2 as shown. The gap between the surfaces can be written as,

$$h = z_1 - z_2 = Ax^2 + By^2 + Cxy \tag{2}$$

where

$$C = \frac{1}{2}\left(\frac{1}{R_2'} - \frac{1}{R_2''}\right)\sin 2\beta - \frac{1}{2}\left(\frac{1}{R_1'} - \frac{1}{R_1''}\right)\sin 2\alpha \tag{3}$$

By a suitable choise of axes we can make C zero, so that

$$h = Ax^2 + By^2 \tag{4}$$

is satisfied by the triangle shown in Fig. 2b, with the result:

$$\begin{aligned} B - A &= \frac{1}{2}\left(\frac{1}{R_1'} - \frac{1}{R_1''}\right)\cos 2\alpha + \frac{1}{2}\left(\frac{1}{R_2'} - \frac{1}{R_2''}\right)\cos 2\beta \\ &= \frac{1}{2}\left[\left(\frac{1}{R_1'} - \frac{1}{R_1''}\right)^2 + \left(\frac{1}{R_2'} - \frac{1}{R_2''}\right)^2 \right. \\ &\quad \left. + 2\left(\frac{1}{R_1'} - \frac{1}{R_1''}\right)\left(\frac{1}{R_2'} - \frac{1}{R_2''}\right)\cos 2\theta\right]^{1/2} \end{aligned} \tag{5}$$

Finally

$$A + B = \frac{1}{2}\left(\frac{1}{R_1'} + \frac{1}{R_1''} + \frac{1}{R_2'} + \frac{1}{R_2''}\right) \tag{6}$$

from which the values of A (=1/2R') and B(=1/2R") can be found.

Denoting the significant dimension of the contact area by a, the relative radius of curvature by R, the significant radii of each body by R_1 and R_2 and the dimensions of the bodies both laterally and in depth by l, we may summarise the assumptions made in the Hertz theory as follows:

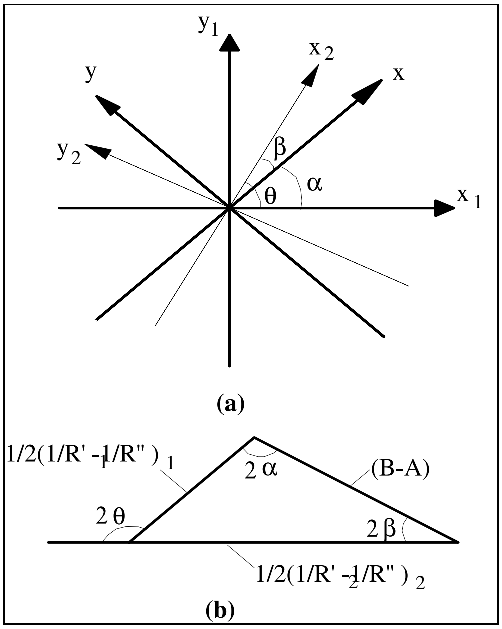


Figure 2 Direction of axes of contact a)sets of axes, b)triangle of contact radius.

- The surfaces are continuous and non-conforming: a®R
- The strains are small:a®R
- Each solid can be considered as an elastic half space: a®$R_{1,2}$, a®1
- The surfaces are frictionless: q_x=q_y=0.

As summaries of Hertz elastic contact stress formulae are given as follows:

$$E^* \equiv \left(\frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2} \right)^{-1} \quad (7)$$

$$R \equiv \left(1/R_1 + + 1/R_2 \right)^{-1} \quad (8)$$

(a) Line contacts (load N per unit length)

Semi-contact width:

$$a = \left(\frac{4NR}{\pi E^*} \right)^{1/2} \quad (9)$$

Max. contact pressure:

$$p_0 = \frac{2N}{\pi a} \left(\frac{NE^*}{\pi R} \right)^{1/2} \quad (10)$$

Max. shear stress:

$$\tau_1 = 0.3 p_0 \quad at \quad x = 0, \quad z = 0.78a \quad (11)$$

(b) Circular point contacts (load N)

Radius of contact circle:

$$a = \left(\frac{3NR}{4E^*} \right)^{1/3} \quad (12)$$

Pressure distribution and max. contact pressure:

$$p = p_0 \left[1 - r^2/a^2 \right]^{1/2}, \quad p_0 = \left(\frac{3N}{2\pi a^2} \right) = \left(\frac{6NE^{*2}}{\pi^3 R^2} \right)^{1/3} \quad (13)$$

Approach of distant points:

$$\delta = \frac{a^2}{R} = \left(\frac{9}{16} \frac{N^2}{RE^{*2}} \right)^{1/3} \quad (14)$$

Max. shear stress:

$$\tau_1 = 0.31 p_0 \quad at \quad r = 0, \quad z = 0.48a \quad (15)$$

Max. tensile stress:

$$\sigma_r = \frac{1}{3} (1 - 2\nu) p_0 \quad at \quad r = a, \quad z = 0 \quad (16)$$

The stress distribution at the surface along the axis of symmetry is given in Fig. 3.

(c)General point contacts (load N)
a=major semi-axis; b=minor semi-axis; c=$(ab)^{1/2}$; R' and R" are major and minor relative radii of curvature; equivalent radius of curvature R_e =$(R' R")^{1/2}$

$$a / b \approx (R' / R'')^{2/3} \quad (17)$$

$$c = (ab)^{1/2} = \left(\frac{3NR_e}{4E^8} \right)^{1/3} F_1(R' / R'') \quad (18)$$

Max. contact pressure:

$$p_0 = \left(\frac{3N}{2\pi ab} \right) = \left(\frac{6NE^{*2}}{\pi^3 {R_e}^2} \right)^{1/3} \left[F_1(R' / R'') \right]^{-2/3} \quad (19)$$

Approach of distant points:

$$\delta = \left(\frac{9}{16} \frac{N^2}{R_e E^{*2}} \right)^{1/3} F_2(R'/R'') \qquad (20)$$

The functions $F_1(R'/R'')$ and $F_2(R'/R'')$ are plotted in Fig. 4, and values of max. shear stress are given in Table 4. When the Hertz equations are applied to the specific examples, we obtain the results shown in Fig. 5.

Table 4 The Maximum Shear Stress Occurs on the z-axis at a Point Beneath the Surface

b/a	0	0.2	0.4	0.6	0.8	1.0
z/b	0.785	0.745	0.665	0.590	0.530	0.480
$(\tau_1)_{max}/p_0$	0.300	0.322	0.325	0.323	0.317	0.310

5.CONCLUSIONS

Although the contact mechanics has its complexities, it has certain basic similarities with other aspects of mechanical engineering in which stress/strain analysis forms the basis of design. Thus, since in general creep and fatigue become increasingly significant as the design load approach to the limiting load, N_1. The theory given here is important in two aspects. On a miniature scale, it provides the nature of asperity contacts. On a macroscopic scale, the theory is important in the analysis of nonconforming machine elements.

Application of contact mechanics has been widely used to solve many mechanical problems, such as the solution of stresses induced by and arbitrary axisymmetric pressure distribution (Hills and Sackfield, 1987).

The stress distribution in the contact region has been investigated by means of contact theory (Olver, et al., 1986) and its effect is investigated in contact fatigue (Cretu, and Popinceanu, 1985).

Clearly any study of tribology must incorporate a detailed understanding of the mechanics of contact of solid bodies (Ioannides and Kuijpers, 1986, Ihara, et al., 1986a, (Ihara, et al, 1986b. This involves an understanding of the nature of the associated deformations and the stress induced by any applied loading to bodies of a wide variety of geometric shapes (Tallian, 1993). The near surface stresses are important because they may result in micropitting, an thus wear.

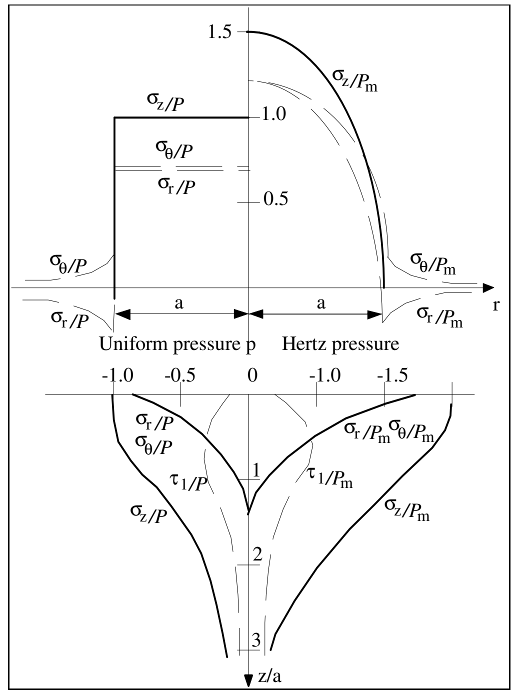


Figure 3 Stress distributions at the surface along the axis of symmetry caused by (left) uniform pressure and (right) Hertz pressure acting on a circular area radius a

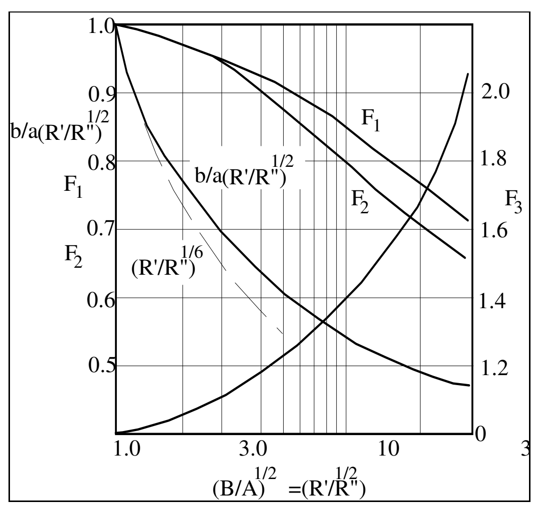


Figure 4 Contact of bodies with general profiles. The shape of the ellipse b/a and the functions F_1, F_2, and F_3 $(=F_1^{-2/3})$ in terms of the ratio (R'/R") of relative curvatures

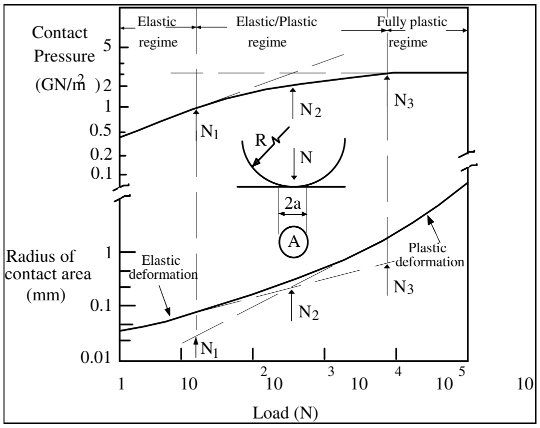


Figure 5 Conditions of contacts as a function of the normal load

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