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INFLUENCE OF ABRASIVE PARTICLE GEOMETRY AND MATERIAL ON THE ABRASIVE WEAR MODE

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Summary:
The abrasive wear is surface damage induced by solid abrasive particles in machine elements contact. Mechanical acting of abrasive particles on the contacting surfaces depends on its shape, size and strength. Qualitative and quantitative analysis of influence of particles geometry and strength on the deformation, which precede abrasive wear, is carried out in this paper. Brittle non-metal particles with spherical, cubical and conical form are considered. Results of carried out analysis can be used in mathematical modeling of abrasive wear.

Keywords: *abrasive wear, abrasive particles, micro plowing, micro cutting*

1. INTRODUCTION

The abrasive wear is surface damage of sliding or rolling contact surfaces due to acting of abrasive particles present in the contact zone. Due to interaction of particles and contact surfaces different stress-strain states are possible, depending on particle shape and size, as well as relation between mechanical properties of particles and contact surfaces. Consequently, the abrasive wear can be based on deformations or cutting. In mathematical modeling of abrasive wear, different authors have been used different models of abrasive particle form: spherical [2,3,4], cubical [5,6] or conical [7]. However, difference in particle shape results in differences in wear modes.

The criterion for determining of abrasive wear mode given in [1] for spherical particle is derived for cubical and conical particle and the analysis of obtained expressions is carried out in this paper.

2. ABRASIVE WEAR MODES

The hard abrasive particle, in its passage through a contact between sliding or rolling surfaces (Fig.1), can induce several physically different surface damages [1]:

- micro plowing;
- micro cutting;
- micro fatigue, and
- micro cracking.

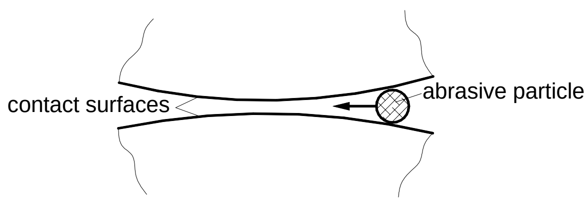


Figure 1. *Abrasive particle entry in contact zone*

In the case of micro plowing, the abrasive particle for single pass along sliding distance makes micro groove on the contacting surface by plastic deformation and without detachment of material from the wearing surface. Deformed material is displaced on sides of the groove, as shown on the Fig.2a.

At the micro cutting, the grooves are formed on the contacting surface due to acting of particle sharp edges. In this case, all groove material is detached, i.e. the lost volume is equal to the volume of the wear grooves (Fig.2b).

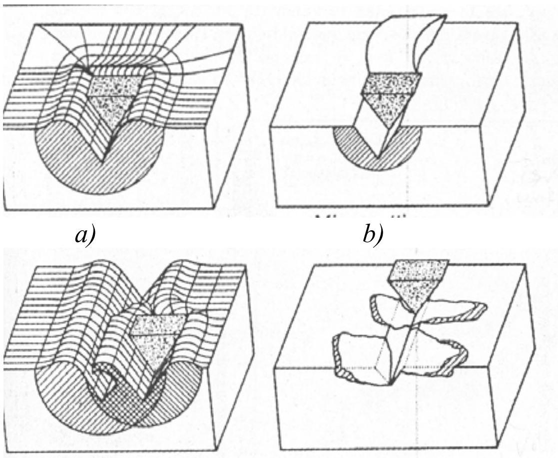


Figure 2. *Abrasive wear modes [1]*

Multiple micro plowing as a consequence of repeated action of single particle or one/many actions of many particles can cause detachment of material due to low cycle fatigue, i.e. micro fatigue (Fig.2c).

Micro cracking occurs when highly concentrated stresses are imposed by hard abrasive particles, particularly on the surface of brittle materials. Due to high stress, concentration cracks on contacting surface are formed and propagated very rapidly. Consequently, large wear debris is detached from wearing surface (Fig.2d).

Micro plowing, micro cutting and micro fatigue dominate in ductile materials while micro cracking is inherent in brittle materials.

The only two interactions of abrasive particles with wearing surfaces are considered in this paper: micro plowing and micro cutting. The micro crushing is not considered, because of its appearing in brittle materials while the most used material in machine constructions is the steel, which is ductile material. The micro fatigue is not considered too, because it is cause of multiple micro plowing.

2. CRITERION FOR DETERMINING THE ABRASIVE WEAR MODE

An abrasive particle found near the contact between lubricated sliding or rolling surfaces (gear teeth, rolling elements and raceways of bearing etc.) is entrained further into the contact zone by friction forces. The passage through the contact zone of abrasive particles which size is smaller than oil film thickness is unobstructed. Larger particles passing contact zone can induce indentations of contacting surfaces as furrows (due to plastic deformation) or scratches (due to cutting). Mode of surface damage subjected by abrasive particle depends on its geometric and mechanical properties.

For further considerations, it is assumed that abrasive particles are of non-metal material with high hardness. Particles keep their form and size during passage through the contact zone, i.e. they are not deformed and crushed. The form of abrasive particles is spherical, cubical and conical (Fig.3).

Figure 3. *Abrasive particle shape: a) spherical; b) cubical; c) conical*

3.1 Spherical abrasive particle

Maximal penetration depth $h_{\max}$ of abrasive particle with radius R (Fig.4) into the contacting surface is determined by depth h_{cr} appropriate to failure (crushing) of particle. On the basis of condition

$$\frac{h_{\max}}{R} = \frac{h_{cr}}{R},$$

it is possible to determine nature of dominant deformations, which precede abrasive wear [2].

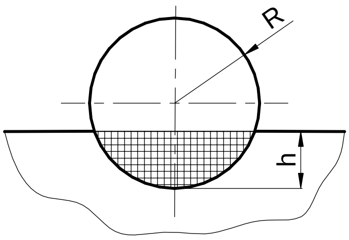


Figure 4. *Spherical abrasive particle*

An abrasive particle is crushed at condition

$$F_{cr} = F, \qquad (1)$$

where:

F_{cr} – crushing load of abrasive particle with radius R;

F – normal load of abrasive particle.

Critical load under which the abrasive particle is crushed can be determined as:

$$F_{cr} = \sigma A = \sigma R^2 \pi \, , \qquad (2)$$

where:

σ – critical crushing stress appropriate to abrasive particle strength.

Normal load in the contact of abrasive particles with wearing surfaces is expressed [2]:

$$F = A_r H = 2\pi R h H \, , \qquad (3)$$

where:

A_r – real contact area (area of arch surface with height h);

h – penetration depth of abrasive particle into the contacting surface;

H – hardness of contacting surface.

Substituting Eq.(2) and (3) in Eq.(1) for the moment when the abrasive particle is crushed, i.e. $h = h_{max} = h_{cr}$ the following expression can be written:

$$\frac{\sigma}{2H} = \left(\frac{h}{R}\right)_{max} \, . \qquad (4)$$

Maximal value of h/R ratio, expressed through the abrasive particle strength σ and wearing surface hardness H is criterion for determining of abrasive wear mode.

3.2 Cubical abrasive particle

Cubical abrasive wear with size a is shown in the Fig.5. Because of comparison with spherical particle, the following equation is introduced:

$$a = R\sqrt{2} \, . \qquad (5)$$

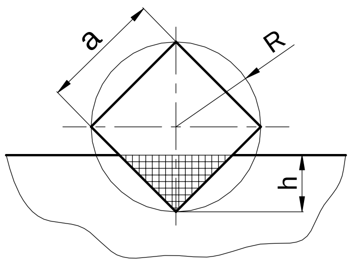


Figure 5. *Cubical abrasive particle*

Critical crushing load of cubical abrasive particle (Fig.6a) with strength σ can be determined by expression:

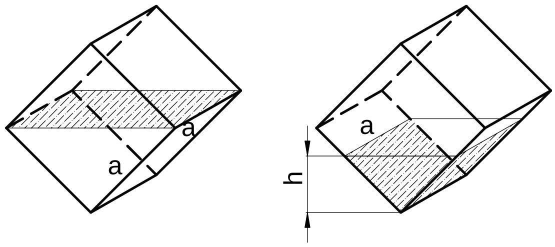
$$F_{cr} = \sigma A = \sigma a^2 \sqrt{2} \, . \qquad (6)$$

Normal load of abrasive particle in contact zone can be determined on the basis of real contact area (Fig.6b) A_r and hardness of wearing surface material H:

$$F = 2ahH\sqrt{2} \, . \qquad (7)$$

Introducing Eq.(6) and (7) in Eq.(1) the following equation can be written:

$$\frac{\sigma}{2H} = \left(\frac{h}{a}\right)_{max} \, . \qquad (8)$$



a) *b)*

Figure 6. *Areas for calculation of: a) critical load; b) operational load*

As in the previous case, deformation which precede abrasive wear, i.e. abrasive wear mode can be determined on the basis of ratio of penetration depth h to nominal size of cubical abrasive particle a.

3.3 Conical abrasive particle

Conical abrasive particle with angle θ and height H_c equal to radius R of imaginary sphere is shown in the Fig.7. Radius of the basis of this cone is given by expression:

$$r = H_c \mathrm{tg}\frac{\theta}{2} \, .$$

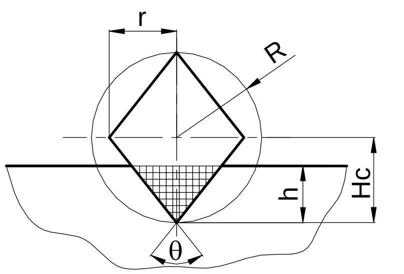


Figure 7. *Conical abrasive particle*

Critical crushing load of conical abrasive particle is:

$$F_{cr} = \sigma A = \sigma r^2 \pi = \sigma H_c^2 \mathrm{tg}^2 \frac{\theta}{2} \pi \, . \qquad (9)$$

Expression for normal load of abrasive particle in contact zone can be written in the following form:

$$F = HA_r = Hh^2 tg\frac{\theta}{2}\pi\sqrt{tg^2\frac{\theta}{2}+1} \, , \qquad (10)$$

where the real contact area between abrasive particle and wearing surface A_r is area of cone with pick angle θ and height h (Fig.7).

Equating expressions (9) and (10) the following expression can be written:

$$\frac{\sigma}{2H} = \frac{1}{2}\left(\frac{h}{H_c}\right)^2 \sqrt{1 + \frac{1}{\mathrm{tg}^2 \frac{\theta}{2}}} \qquad (11)$$

4. DISCUSSION

Evaluation of the nature of dominant deformation, which precedes abrasive wear, can be made on the basis of Eq.(4). Namely, the boundary value of h/R ratio between elastic and plastic deformations is $(h/R)_{el\text{-}pl} = 10^{-2}$, and between plastic deformations and cutting $(h/R)_{pl\text{-}c} = 0{,}3$ (for lubricated surfaces) [2].

Table 1. *Calculation of* $(h/R)_{max}$ *ratio*

Material of abrasive particle	Quartz	Corundum
Strength of abrasive particle σ N/mm^2	100...700	700...1300
Material of wearing surface	Steel	
Hardness of wearing surface H N/mm^2	2000...6000	
$(h/R)_{max}$	0,008...0,175	0,050...0,325

Mechanical properties of wearing surface material (steel) and abrasive particles material (quartz and corundum) are given in Table 1. The $(h/R)_{max}$ ratio is calculated on the basis of this data and its values indicate plastic deformations as dominant. Appearance of elastic deformations or cutting is possible only with combination of extreme abrasive particles strength and wearing surfaces hardness. Consequently, probability of these cases is negligibly small.

Comparing equations (4) and (8) with respecting Eq.(5), the following expression can be written

$$h_{\text{cube}} = h_{\text{sphere}}\sqrt{2}$$

which is to say that penetration depth of cubical abrasive particle can be 1,41 times larger than penetration depth of spherical abrasive particle. Consequently, the probability of occurrence of micro cutting is increased.

While the functions (4) and (8) are very simple, the function (11) is complex and non-linear. However, the form of function shows much greater maximal penetration depth of conical abrasive particle in relation to penetration depth of cubical or spherical abrasive particle, particularly in the case of greater angle θ.

5. CONCLUSIONS

From the obtained theoretical results, the following conclusions can be made:

- evaluation of dominant abrasive wear mode can be carried out on the basis of geometric and mechanical properties of abrasive particles;
- spherical abrasive particles cause plastic indentations on the contacting surface mainly (micro plowing);
- cubical or conical abrasive particles depending on its strength can cause both micro plowing and micro cutting, but micro cutting is dominant;
- results of carried out theoretical analysis request experimental verification and than can be used for mathematical modeling of abrasive wear.

REFERENCES:

[1] Zum Gahr, K.H.: Wear by hard particles, I World Tribology Congress, London, 1997

[2] Ямпольский, Г.Я., Крагельский, И.В.: Исследование абразивного износа элементов пар трения качения, Наука, Москва, 1973

[3] Кудиш, И.И.: Расчет износостойкости и усталостного выкрашивания подшипников качения под осевой нагрузкой, Сборник научных трудов ВНИПП, №2, Москва, 1988

[4] Karamis Baki, M.: A model on wear behavior of metallic materials working in free abrasive media, 2nd International Conference on Tribology, Thessaloniki, 1996

[5] Dwyer-Joyce, R.S.: Predicting the Abrasive Wear of Ball Bearing by Lubricant Debris, Wear, Vol.233-239, 1998, pp.692-701

[6] Dwyer-Joyce, R.S., Sayles, R.S., Ioannides, E.: An investigation into the mechanisms of closed three-body abrasive wear, Wear, 175, 1994, pp.133-142

[7] Hisakado, T., Tanaka, T., Suda, H.: Effect of abrasive particle size on fraction of debris removed from plowing volume in abrasive wear, Wear, 236, 1999, 24-33