Transport and Engineering. Production Technologies

2013 / 35

Review of the Wear Process

Vera Kulakova[1], Oskars Lininsh[2], [1-2] *Riga Technical University, Institute of Mechanical Engineering*

***Abstract* – The article describes the current understanding of the physical processes of tribology occurring in the material of the surface layer under the influence of friction, leading to its destruction. The main way of destruction of the material on the friction surfaces at different types of wear is formation and accumulation of damages in thin surface layers of the material. Accumulation of structural defects concentrating in the surface layer is the consequence of this process.**

***Keywords* – friction, roughness, wear intensity.**

I. INTRODUCTION

Relative displacement of contact surfaces and their mechanical interaction change not only the position of surface layers and material properties, but also cause their destruction.

Ordinary destruction looks like separation of little material particles from friction surfaces, which in the course of time leads to the changes of form and size of contacting details. Such phenomenon is called wear.

The main cause of wear is deformation of contact surface material under the influence of contact stress and temperature fluctuations. They lead to the accumulation of structure defects in surface layers.

The size of wear is determined by length, volume, mass units, but wear per time unit - by wear rate m/h [1-3]

$$J = \Delta h / t \,, \qquad (1)$$

where *Δh*- size of wear (linear wear), or thickness of the removed layer, m; *t*- time, h

Another wear characteristic - wear intensity is widely applied.

$$J = \Delta h / L \text{ (dimensionless quantity)} \qquad (2)$$

where *Δh* – value of wear, m; *L* – friction path, m.

A short review of the varieties of wear provides insights into types of wear.

Fatigue wear

Fatigue wear occurs when there are no abnormal damages during the work of friction_units (dripping, scoring, micro-cuts and so on), friction takes place under normal circumstances, surfaces are greased, however, due to the friction of surface layers the material "gets tired" and begins to separate as wear particles. Two kinds of wear are distinguished: multi-cyclic and small-cyclic.

Abrasive wear

Abrasive particles effect breakdown action on the friction surfaces in two ways. Sharp abrasive particles scratch, causing chaotic micro-cutting process. Another characteristic mechanism of wear is deformation operation of “blunt” abrasive particles, which do not scratch, but hollow out craters or furrows, and being repeated many times, cause local fatigue damages.

A typical wear process in time is presented in Fig.1.

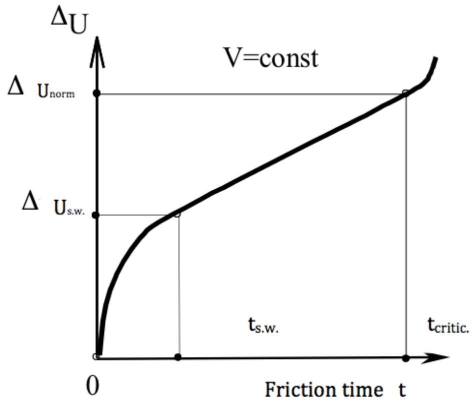


Fig.1. Wear curve

During the alignment stage the curve characterizes a starting work period ($t_{s.w.}$). Then wear goes on at constant rate ($t_{s.w.}$, t_{critic}). This part is called a normal operation period. If $t > t_{critic.}$ wear rises sharply and becomes disastrous, as a result the friction unit fails.

During the alignment stage friction unit operation properties are formed.

The roughness formed at the end of the alignment period is called balanced. Balanced roughness is connected with output, but its parameters are mainly determined by the physical and mechanical properties of particle materials and greasing, and also the characteristics of friction mode (load, speed, temperature, etc.). When friction units are put into operation after manufacturing or capital repair, the technical documentation carefully sets the alignment or run-in modes, so that it is done in the shortest time possible and would create favorable conditions for long-term operation. Usually the allowable limiting value of wear is also specified (Δhmax), which determines the service life of the whole friction unit or replaceable details.

The main mode of material break-down on friction surfaces at all kinds of friction is creation and accumulation of damages in thin material surface layers. So, the presence of abrasive, chemical transformations or transport phenomena can only change the intensity of damage either towards acceleration or reduction.

II. FRACTOGRAPHY OF FRICTION

When studying the relief of worn down surfaces and structural characteristics of surface layer of materials, optical and electron microscopy is widely used [4].

Optical microscopy most often is used for getting a picture of size and distribution of structural constituent parts of the material using the photos of polished and slightly pickled areas of surfaces of components or material samples. Being aware of the magnification of photos it is easy to measure the size of grains and their constituent parts. The best optical microscope magnification reaches 1,000. Examples of optical and electronic photos of worn surfaces are shown in Fig.2.

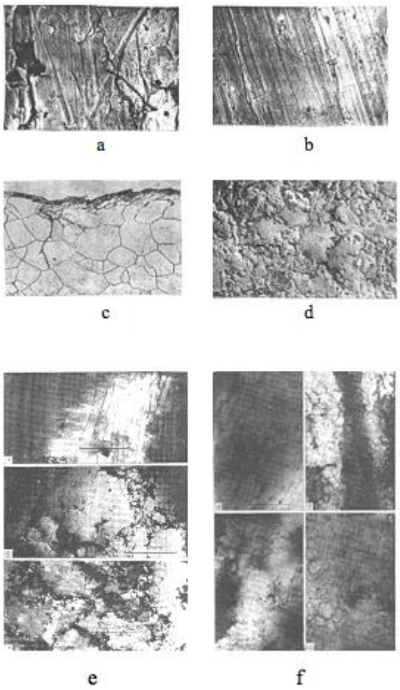


Fig.2. Optical and electronic (x10000) photos of worn surfaces
a –cast-iron; b – steel ragged surface; c – fatigue cracks (slanting cut); d – surface damaged by fretting corosion; e – copper dislocation structure development; f- fatigue development at iron crystal friction

Electronic microscopes allow getting a much stronger magnification – up to 500,000 times and more.

Electronic microscopes allow taking photographs “on transmission”, if thin film structure and position are examined, and at reflection. The scanning electron microscope (REM) works in the reflection regime.

REM method is widely used in the observation of surface topography, for example, if the surface includes secondary structure film islets, then after the shading of replicas under the given angle a photo allows determining the thickness of these films.

A wide choice of methods for structural analysis is based on the X-ray diffraction, electrons and neutrons, which can be directed to the investigated object.

In the X-ray structural analysis beams with the wavelength in the range 0.05 ÷ 0.25 nm are used that are commensurable with interatomic distances in solid bodies and liquids, which allows them to pass through objects opaque to light rays. Passing through a solid substance X-rays diffract on the crystal lattice atoms. The maximum condition is described by Bragg formula:

$$n\lambda = 2d\sin\theta \tag{3}$$

where d – distance between the neighboring parallel atomic planes of the crystal;
θ - angle of slide;
λ - X-ray radiating wave length;
n – maximum order.

The diffraction patterns are obtained on X-ray photographs by photographic method of registration in Debye-Scherrer cameras or in diffractograms with automatic registration by counters of registration of X-ray scattering intensity. The diffraction pattern generally helps to determine and assess, considering qualitative and quantitative aspects, the changes of the phase composition of materials of friction pairs, inter-plane distances in the phase crystal lattice at diffusion redistribution of alloying elements and formation of solid solutions, changes of condition of thin crystalline structure of friction deformed surface layers of metals, alloys, etc.

III. CONCEPTUAL APPROACH

Using various concepts for wear modeling has led to the creation of half-empirical expressions, which recently have been used as the main basis for calculations to make wear estimations. First of all, it is connected with easily available use of gained dependences and, secondly, with a possibility of qualitative and quantitative analyses of the wear process.

At the basis of these models, often built on physical considerations taking into account the dimensional theory, are the following assumptions:

- wear is proportional to the path of friction;
- wear is proportional to the friction work force;
- wear is determined by physical parameters of the process and mechanical properties of materials.

V.D.Kuznecov characterized the wear value of detail or metal sample per a unit of friction work as wear intensity J [5]:

$$J = \frac{V}{\mu \cdot P \cdot L} \tag{4}$$

where V – wear of solid body material during experimental period;
μ - coefficient of friction;
P - normal load;
L – friction path.

Due to the difficulty of definition of the work of friction force for the calculation of wear intensity the expression (4) is more often used in the form

$$J = J_0 \cdot \mu = \frac{V}{P \cdot L} \tag{5}$$

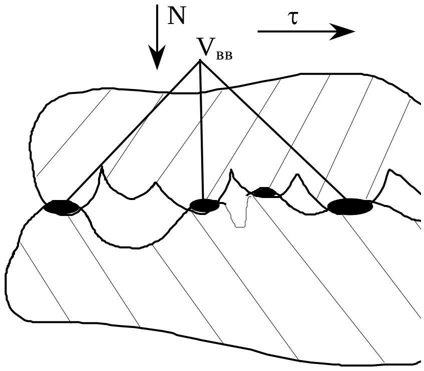
The equation for wear calculation got by Archard has similar character [6]:

$$U = k\frac{P \cdot L}{H} \tag{6}$$

where k – coefficient of wear ;
H - hardness.

Supposing that wear is similar to small sequencing fatigue, Chalen suggested to use empiric equation of Manson-Koffin for the analysis of destruction and got the expression for the calculation of the coefficient of wear:

$$k_1 = \frac{9 \cdot \sqrt{3r} \cdot \mu}{n \cdot \gamma_t} = \frac{9 \cdot \sqrt{3r} \cdot \mu}{C^D \cdot \gamma_t^{1-D}} \tag{7}$$



where r – relation of plastic work to complete work of friction;
μ - coefficient of friction;
n – number of cycles before destruction;
C,D – constants of material;
γ_t – increase of deformation per loading cycle.

D.G. Evan and D.K.Lankaster [7] offered a new, easier type of D.Archard's wear equation :

$$U = k \cdot P \cdot L \tag{8}$$

where k – size coefficient of wear.

Although this model is frequently used, its practical application poses some problems. In particular, sufficiently reliable methods of estimation of wear coefficient are not available until now. The influence of different combinations of materials, modes of operation, environments, etc. often leads to large discordance in the results got by calculation and experimental data.

I.V.Kragelsky offered his own concept, which can be formulated as follows: wear is proportional to the volume of mutual introduction of roughness *Vвв.*

This concept is illustrated by the arbitrary section of contact of rough ground bodies in Fig.3.

In the above picture in Fig. 3 it is possible to unequivocally list what determines the volume of mutual introduction: properties of materials, load, and parameters of roughness, greasing and other.

In accordance with the theory by I.V.Kragelsky there is offered the base equation of wear, which implies the fatigue mechanism of destruction of surfaces, similar to small sequencing fatigue. The measure of influence in his approach is a number of cycles of loading n.

Briefly the solution of the basic equation of I.V.Kragelsky leads to the following.

The concept of specific wear is introduced:

$$i_n = \frac{\delta V}{A_r d} \tag{9}$$

where i_n – the value of material wear at the movement of a mobile component on a distance equal to the average diameter of the contact stain d, calculated per unit of f_{pk} and a unit of past path.

As $\delta V = \delta h{\cdot}Ar$, then $i = \delta h/d$, Ar - fpk, δh –thickness of worn layer in the specified movement displacement to a distance equal to the average diameter of the stain, f_{pk} fails and then restores. Therefore, on the sliding path L contact field is restored n times, i.e.

$$n = L/d \tag{10}$$

At the end of the path the wear value is:

$$\Delta V = \delta V \cdot n \tag{11}$$

As wear intensity $J = \Delta V/LS$, then, assuming that S – friction area is equal to contour area (Ac) or, if there is no waviness, to nominal contact area (Aa), one can record

$$J = \Delta V / LA_a \tag{12}$$

Let us compile relation J/i using formulas (10, 11, 12):

$$\frac{J}{i} = \frac{\Delta V \cdot d}{\delta V \cdot L} \cdot \frac{A_r}{A_a} \tag{13}$$

However, according to (10, 11) formula $\Delta V / \delta V = L/d = m$. Therefore

$$J = i(A_r / A_a) \tag{14}$$

Let us calculate the value of the deformed material. We express the cross-sectional area of rough layer on a distance from its upper side:

$$A_s = A_{SO}\left(\frac{1}{R_p}\right)^{\nu} = n_{oa}\Delta A_s A_s\left(\frac{1}{R_p}\right)^{\nu} \tag{15}$$

Here, as was mentioned earlier, it is assumed that $As=Aa$. Deformed material volume

$$\Delta V_D = \int_0^a A_s \cdot da = \left(\frac{A_{S0}}{R_p^v}\right)\int_0^a a^v da = \frac{A_{S0}}{(v+1)R_p^v} a^{v+1} \qquad (16)$$

The value of the volume separated due to wear during one breakdown of friction-link constitutes

$$\delta V = \frac{\Delta V_D}{m} = \frac{A_{S0} \cdot a^{v+1}}{(v+1)R_p^v \cdot m} = \frac{t_m R_p}{m(v+1)} \varepsilon^{v+1} A_a \qquad (17)$$

Here $t_m = A_{so}/A_a$;
$\varepsilon = a/R_p$;
$A_r = \alpha A_s$.

Specific wear

$$i = \frac{\delta V}{A_r \cdot d} = \frac{R_p \cdot \varepsilon}{\alpha \cdot m(v+1)d} = \frac{a}{\alpha \cdot m(v+1)d} \qquad (18)$$

The average area of cut knuckle remote by plane from the top boarder of rough layer is found:

$$\Delta A_s = \frac{A_s}{n} = \frac{A_{S0} \cdot a}{n_0 \cdot R_p} = \frac{2\pi r a}{v} \qquad (19)$$

If we count approximately that $\Delta A_s \cong \pi d^2 / 4\alpha$, then the average diameter of contact stain is: $d = 2\sqrt{\alpha \Delta A_s}\sqrt{\pi}$. Inserting formula (19) in this expression, we get

$$d = 2\sqrt{2\alpha} \cdot \sqrt{ra/v} \qquad (20)$$

Considering (18, 20) the specific wear is

$$i = \frac{\sqrt{v}}{2\sqrt{2}\alpha^{3/2} n(v+1)}\sqrt{\frac{a}{r}} \qquad (21)$$

The wear intensity is

$$i = \frac{a}{\alpha \cdot m(v+1)d}\sqrt{\frac{A_r}{A_a}} \qquad (22)$$

The difficulty of using formula (22) is caused by the necessity to determine the critical number of cycles of loading leading to the damage of surface element m. Therefore, it was proposed to use the regularity of fatigue damage in the cyclic tension. This law is described by the Weller formula:

$$n = \left(\frac{\sigma_0}{\sigma}\right)^t \qquad (23)$$

where σ_0 – stress leading to damage during one loading cycle (n=1);
σ - active stress;
m – number of cycles leading to rod damage;
t – exponent changing depending on the properties of materials tested within the range from 3 to 14.

Stress is connected with the actual pressure on the contact and friction coefficient by equation [8].

$$\sigma = k\mu\sigma\gamma = k\mu N / A_\gamma \qquad (24)$$

Coefficient $\kappa = 3 \div 5$, depending on the nature of material.

Despite the shortcomings, the presented models are still interesting, and evaluation methods of parameters of these models are being continuously developed.

IV. CONCLUSION

Analyzing the parts for presence of wear it is necessary to be guided by three basic assumptions:

- there is a proportion between wear and sliding distance;
- there is a proportion between wear and work of force friction;
- wear is characterized by the physical parameters of the process and the mechanical properties of materials.

In wear calculation it is obligatory to take into account all of the aforementioned points.

REFERENCES

1. **Kragelsky I., Alisin V.** "*Tribology – Lubrication, Friction and Wear*," Mir publishers, Moscow, 2001.
2. **Kragelsky I.V., Dobichin N.M., Kambalov V.S. "***Osnovi raschetov na trenie i iznos"*. Moskva: Mashinostroenie, 1977. – 526 str.
3. **F.P.Bowden, A.D.Yoffe.** "*Fast Reactions in Solids"*, Butterworths Scientific Publications, London 1958, 164 pp.
4. **Berkovich I.I., Gromakovsky D.G.** *"Tribologija. Uchebnik dlja vuzov"*, Samara: Samar. Gos. The. Un-t, 2000. – 268 str.
5. **Kuznecov V.D.** *"Fizika tvjordogo tela",* Tomsk: T.4, 1947. – 542 str.
6. **Archard J.F. "***Contact and Rubbing of Flat Surfaces"*. J. Appl. Phys., vol. 24, N 8, 1953, pp. 981-988.
7. **Lancaster J.K. "***Abrasive Wear of Polymers"*. Wear. vol. 14, 1969, pp. 223-239.
8. **Fleischer G.** "*Verschliss und zukerlassigkit veb"*/ Fleischer G., Groges H., Thum H. – Berlin: Verlag Technik, 1980, 244 p.

Vera Kulakova graduated from Riga Technical University in 2007, where she got a Bachelor Degree in production technology. In 2009 she got an engineering academic Master's Degree in mechanical engineering technology.

Scientific work started in 2009, when she worked as a researcher at Riga Technical University. She has published 10 publications on her work in different scientific publishing houses. Also she has participated in 7 international conferences.

At present she is a doctoral student at RTU/ Production Technology (direction – device engineering). T Her major is resistance welding.

Oskars Lininsh graduated from Riga Polytechnic Institute (now RTU) in 1965, where he got an engineering degree in production technology. He obtained a PhD Engineering Degree in the field of friction and wear in machines at RTU in 1992.

His scientific work started in 1966, when he worked as an assistant at Riga Polytechnic Institute. From 1970 the author started his pedagogical work and since 1973 he continued as a professor assistant in Riga Technical University. In 2001 he was elected associate professor and in 2008 - a professor at RTU Institute of Machine Building. At the same time he worked as the Secretary of Science in the Commission of Production Technology and currently he is the Secretary of the Council of the Faculty of Transport and Mechanical Engineering

The main research fields are calculations of friction and wear in machines and design of apparatuses.

Vera Kulakova. Oskars Liniņš. Nodiluma procesa pārskats.

Rakstā ir izklāstīti triboloģijas mūsdienīgie priekšstati par fiziskiem procesiem, kas notiek uz materiāla virsmas slāņa berzes iespaidā, kas noved pie tā iznīcināšanas. Jāsaprot, ka nodilums ir sarežģīts daudzpakāpju process. Galvenais dilšanas iniciators ir kontaktējošo līmeņu materiāla deformācija kontaktu spriegumu darbības un temperatūru fluktuācijas rezultātā. Tas izraisa struktūras defektu uzkrāšanos ar koncentrāciju virspusējā kārtā. Pie tam abrazīvu, ķīmisku pārvērtību vai pārnesuma parādības esamība var tikai izmainīt iznīcināšanas intensitāti paātrināšanas vai palēnināšanas virzienā. Jāatzīmē, ka tīrā veidā dilšanas mehānisms praktiski nav sastopams, visbiežāk pārsvarā ir noteicošais dilšanas mehānisms un attiecīgās formas atkarībā no konstrukcijas un berzes mezgla darba apstākļu īpatnībām.

Вера Кулакова. Оскарс Линыньш. Обзор процесса изнашивания.

В статье изложены современные представления трибологии о физических процессах, протекающих в материале поверхностного слоя под действием трения, ведущих к его разрушению. Следует иметь в виду, что изнашивание является сложным многоуровневым процессом. Основным инициатором изнашивания является деформация материала контактирующих поверхностей под действием контактных напряжений и температурные флуктуации. Их следствием является накопление дефектов структуры с концентрацией в поверхностном слое. При этом наличие абразива, химических превращений или явления переноса может лишь изменять интенсивность разрушения либо в сторону ускорения, либо замедления. Следует отметить, что в чистом виде механизм изнашивания практически не встречается, чаще всего преобладает ведущий механизм изнашивания и сопутствующие формы в зависимости от особенностей конструкции и условий работы узла трения.