Predicting the Intensity of Abrasive Wear Based on the Fatigue Hypothesis

Vsevolod Bulych¹, Svetlana Golubina^{1,}, Maxim Semenov¹, and Alexey Korzhikov¹.*

¹Kaluga Branch of Federal State Budgetary Educational Institution of Higher Education “Bauman Moscow State Technical University (National Research University)”, Kaluga, Russian Federation

Abstract. The mechanism of surface fatigue failure during abrasive wear is considered. Mathematical dependences connecting the wear conditions with its intensity are obtained. The obtained dependencies make it possible to quantify the wear rate.

It is known that up to 80% of machine parts fail due to wear and tear. Of these, more than 50% are subjected to intense abrasive wear. This explains the large volume of scientific papers [1-5] devoted to the study of the mechanisms of abrasive wear and the factors that affect its intensity. The results of numerous studies [6, 7] show that the wear of metal in an abrasive environment depends on many factors that are complexly related to each other.

It is shown in [6-10] that abrasive wear can occur due to micro-cutting, micro-cracking, tearing out of individual grains and destruction of the surface layer due to fatigue processes. It is widely believed that fatigue wear is characteristic either for rolling friction pairs with intense contact stresses, or for abrasive wear of plastic materials [9, 10]. Thus, the cases of plastic indentation of an abrasive particle into a softer surface are considered in detail. With the relative movement of the abrasive along the surface, it scratches with the extrusion of plastically deformed metal along the edges of the scratch. It is obvious that subsequent acts of plastic deformation will lead to re-hardening of the surface layer and its destruction. The possibility of a fatigue abrasion mechanism in the elastic region of contact between the abrasive and the surface has hardly been investigated.

The mechanism of fatigue wear is considered most fully in [6]. Thus, it is noted that the friction of each micro-protrusion of the mating surfaces forms a wave of material compression in front of itself, and the region of tensile stresses behind itself. During the passage of the micro-protrusion, each point of the mating surface experiences one cycle of alternating loading. Hence, it is concluded that fatigue failure can occur even under the action of elastic stresses in the contact zone of the particle and the surface. Based on the experimentally determined characteristics of the fatigue failure of the surface material, a number of mathematical dependences is obtained that make it possible to predict the wear intensity in both the elastic and plastic regions of contact stresses.

However, these studies were performed in relation to the case of two-body abrasion. The presence of abrasive particles changes the loading conditions of the worn surfaces. First, it is necessary to take into account that the abrasive particle can both slide and roll over the

* Corresponding author: asbina@yandex.ru

surface. The nature of the particle motion will affect the distribution of mechanical stresses in and around the contact. Secondly, the method of determining the actual contact area and contact stresses, based on the use of data on the micro-geometry of the surfaces, is not suitable. Thirdly, due to the deceleration of the movement of particles over the surface of the part, the speed of their relative movement may differ from the speed of movement of the part in the abrasive medium. Fourthly, small abrasive particles can be completely retarded by the macroscopic protrusions of the surface, which can drastically reduce the wear rate. The task of taking into account all these factors is very difficult and requires further experimental research.

In this paper, the possibility of a theoretical description of abrasive wear in the elastic region of contact stresses under the following assumptions are investigated:

- 1 – surface roughness and braking of abrasive particles are neglected;
- 2 – we present the abrasive particle in the form of a ball;
- 3 – we assume that a spherical abrasive particle rolls over the surface when it moves;
- 4 – other destruction mechanisms are assumed to be insignificant.

These assumptions allow us to estimate the maximum possible intensity of abrasive wear as a result of processes.

Suppose that abrasive particle 1 with a radius R is pressed against the wear surface 2 with force F , is pressed into it to a depth d and moves along the surface at a speed v (Fig. 1).

Fig. 1. Calculation scheme of movement of a spherical abrasive particle on the surface

As shown in [6], a compressive stress field appears in front of the particle, and a tensile stress field appears behind it. Thus, when the abrasive particle moves through a certain point A lying on the surface, a single cycle of alternating loading will take place in it. Let us also assume that a surface layer with a thickness equal to the indentation depth of the particle d is subjected to alternating loading.

The depth of indentation (Fig. 1) of the particle is estimated by the well-known formula [11]

$$d = \left(\frac{3F}{4E^* R^{1/2}} \right)^{2/3}, \quad (1)$$

where $\frac{1}{E^*} = \frac{1 - \mu_1^2}{E_1} + \frac{1 - \mu_2^2}{E_2}$, μ_1, μ_2 – the Poisson coefficients of the particle and surface materials; E_1, E_2 – the elastic modulus of the particle and surface materials.

In this case, the maximum voltage in the center of the contact area $\sigma_{\max}$ will be

$$\sigma_{\max} = 0,388 \sqrt[3]{FE^* R^{-2}}. \quad (2)$$

Fatigue wear of the surface will occur if

$$\sigma_{\max} < [\sigma_{-1}], \quad (3)$$

where $[\sigma_{-1}]$ – the limit of the cyclic strength of the wear metal.

According to this assumption, if

$$\sigma_{\max} < [\sigma_{-1}] \quad (4)$$

the intensity of wear will be determined not by the fatigue destruction of the surface, but only by the rate of its oxidation upon contact with wet soil. As a result of friction with the soil, the resulting oxide and hydroxide films will be removed, which will determine the rate of wear.

Let us use the well-known dependence [12] that

$$\sigma_{-1} = (0,4 \dots 0,6) \sigma_B, \quad (5)$$

where σ_{-1} – the limit of the temporary strength of the wear metal.

In what follows, we will take

$$\sigma_{-1} \approx 0,5 \sigma_B. \quad (6)$$

The relationship between $\sigma_{\max}$ and the number of loading cycles N before the destruction of the material will be found from the dependence of the form [12]

$$\ln \sigma_{\max} = a - b \ln N, \quad (7)$$

where a and b – the empirical coefficients.

For specific materials, the coefficients a and b can be taken from reference sources, for example [12, 13]. For preliminary calculations, we find the values a and b as follows. At low-cycle fatigue, the fracture stresses are close to the yield strength of the material σ_t , and the number of cycles does not exceed $N=10^3$. In multi-cycle fatigue, the fracture stresses cannot exceed the fatigue limit $[\sigma_{-1}]$. In this case, the number of cycles of destruction can be taken $N=10^6$. Taking into account the above, we will compose a system of equations for finding the coefficients a and b

$$\begin{cases} \ln \sigma_t = a - b \ln 10^3 \\ \ln [\sigma_{-1}] = a - b \ln 10^6 \end{cases}. \quad (8)$$

Taking $\ln 10^3 \approx 6.91$ and $\ln 10^6 \approx 13.82$ from (8) we find

$$a = \ln \frac{\sigma_t^2}{[\sigma_{-1}]}, \quad (9)$$

$$b = 0,145 \ln \frac{\sigma_t}{[\sigma_{-1}]}, \quad (10)$$

Substituting (9) and (10) into (7) and taking into account (6), we obtain

$$\ln \sigma_{\max} = \ln \frac{2\sigma_t^2}{\sigma_B} - 0,145 \ln \frac{2\sigma_t}{\sigma_B} \ln N. \quad (11)$$

To simplify mathematical calculations, we introduce the notation

$$\alpha = \ln \frac{2\sigma_t^2}{\sigma_B}, \quad (12)$$

$$\beta = 0,145 \ln \frac{2\sigma_l}{\sigma_B}. \quad (13)$$

Then, taking into account (12) and (13), from (11) we obtain the dependence of the number of loading cycles before the destruction of the metal

$$N = \exp \frac{\alpha - \ln \sigma_{\max}}{\beta}. \quad (14)$$

To calculate $\sigma_{\max}$ by formula (2), it is necessary to know the force F acting on one abrasive particle. Assume that

$$F \approx 4pR^2, \quad (15)$$

where p – the pressure of the abrasive on the surface.

We also take into account that the number of loading cycles N depends on the number of abrasive particles that have moved along the wear surface. Then the number of loading cycles n of an arbitrary point of the surface when it is moved in an abrasive medium at a distance of 1 m will be

$$n = \frac{1}{2R}. \quad (16)$$

Considering this, the path of movement L_d of the surface in the abrasive medium, at which the destruction of the surface layer of the part with a thickness of will occur d , will be

$$L_d = \frac{N}{n}. \quad (17)$$

Or after substituting (14) and (16) in (17)

$$L_d = 2R \exp \frac{(\alpha - \ln \sigma_{\max})}{\beta}. \quad (18)$$

The wear rate is estimated as the ratio of the wear value per unit of the surface movement path in the abrasive medium

$$I = \frac{d}{L_d}. \quad (19)$$

After substituting (1), (15), and (18) into (19) and simple transformations, we obtain

$$I = \frac{\left(\frac{3p}{E^*}\right)^{\frac{2}{3}}}{2 \exp \left[\frac{\alpha - \ln \left(0,388 \sqrt[3]{4pE^{*2}} \right)}{\beta} \right]}. \quad (20)$$

Analysis of expression (20) shows that, I in general, it increases nonlinearly with increasing p . Taking this into account, for specific combinations of the base metal and abrasive, dependence (20) can be represented in the form

$$I = Ap^m. \quad (21)$$

where a, m – constants depending on the properties of the base metal and abrasive.

The dependence of this type can be described by numerous experimental data on the intensity of abrasive wear of various steels, given, for example, in [8, 13-15].

At certain values of the physical and mechanical properties of the surface material and abrasive, the dependence of the wear rate on the pressure of the abrasive p can be close to direct proportionality. And then the expression (20) can be written in the known form [13]

$$I = kp. \quad (22)$$

where k – the proportionality coefficient.

According to (22)

$$k = \frac{\left(\frac{3}{E^*}\right)^{1/3}}{2p^{1/3} \exp \left[\frac{\alpha - \ln \left(0,388 \sqrt[3]{4pE^{*2}} \right)}{\beta} \right]}. \quad (23)$$

It can be seen from (23) that k it is determined to a large extent by the physical and mechanical properties of the contacting materials.

Depending on (20), there are no geometric parameters of the abrasive particles, and according to this, the wear rate does not depend on the size of the abrasive particles. It should be noted that experimental studies have established that the wear rate increases with the grain size only up to a certain critical diameter (about 0.05 ... 0.1 mm), and then either slowly increases with the grain size, or remains constant [9]. Thus, the expression (20) in the first approximation does not contradict the experimental results for abrasive fractions greater than 0.1 mm.

A number of authors see the reason for the decrease in the wear rate with a decrease in the abrasive fraction as a decrease in the contact pressure and the protective effect of the fine fraction due to its braking on the surface [9]. However, these processes were excluded from our consideration due to the assumptions made. For the theoretical study of wear in a medium of fine abrasive, a model is required that takes into account the peculiarities of the movement of the abrasive along the wear surface and the distribution of the abrasive pressure over it, depending on the micro - and macrogeometric parameters of the surface.

References

1. Sin, N. Saka and N.P.Suh, *Abrasive wear mechanisms and the grit size effect*, Wear, v. **55**, p. 163-190 (1979)
2. I. Sevim, I.B. Eryurek, *Effect of abrasive particle size on wear resistance in steels*, Materials and Design, v. **27**, p.173–181 (2006)
3. S. Mezlini, M. Zidi, H. Arfa, M.B. Tkaya, P. Kapsa, *Experimental, numerical and analytical studies of abrasive wear: correlation between wear mechanisms and friction coefficient*, C.R. Mecanique, v. **333**, p. 830–837 (2005)
4. K. Hokkirigawa, K. Kato, *An Experimental and Theoretical Investigation of Ploughing. Cutting and Wedge formation During Abasive Wear*, Tribology International, v. **21(1)**, p. 51-57 (1988)

5. M. Saarna, P. Kulu, R. Veinthal and R. Tarbe, *Study of surface fatigue of wear resistant powder metallurgical materials*, Proc. Estonian Acad. Sci. Eng., v. **12(4)**, p. 377-387 (2006)
6. I.V. Kragelsky, *Friction and wear* (Moscow: Mashinostroenie, 1968)
7. D.N. Garkunov, *Tribotechnics* (Moscow: Mashinostroenie, 1989)
8. M.M. Khrushchev, M.A. Babichev, *Abrasive wear* (Moscow: Nauka, 1970)
9. M. Adamiak, *Abrasion Resistance of Materials* (InTech, 2012)
10. Subhankar Das Bakshi, *Wear of fine pearlite, nanostructured bainite and martensite: This dissertation is submitted for the degree of Doctor of Philosophy - Darwin College*, (2016)
11. K. Johnson, *Mechanics of contact interaction* (Moscow: Mir, 1989)
12. V.P. Kogaev, *Calculations for strength under stress, variable in time* (Moscow: Mashinostroenie, 1977)
13. M.M. Tenenbaum, *Resistance to abrasive wear* (Moscow: Mashinostroenie, 1976)
14. 14. A.I. Zimin, S.F. Kamenskikh, *Research on the mechanism of destruction of iron-carbon alloys by abrasive tools*, Universum: tekhnicheskie nauki, v. **4(37)** (2017)
15. V.V. Vinogradov, G.M. Sorokin, M.G. Kolokolnikov, *Abrasive wear* (Moscow: Mashinostroenie, 1990)