UDC 620.178

DURABILITY OF MATERIALS UNDER REPEATED DYNAMIC LOADING

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***Annotation**. The regularities of micro-shock fatigue destruction of annealed metal materials under severe loading conditions are revealed. Based on the law of summation of damages and taking into account the features of crack formation in dynamically deformed volumes of wear materials, a model is obtained for erosion. The generalization of the obtained private model at the micro - macroscale level of wear made it possible to obtain a universal power dependence suitable for assessing the durability of materials. The law of summation of damages for stepped loading is presented .*

***Key words:** crack, wear, erosion, fatigue life.*

ДОВГОВІЧНІСТЬ МАТЕРІАЛІВ ПРИ ПОВТОРНОМУ ДИНАМІЧНОМУ НАВАНТАЖЕННІ

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***Анотація.** Виявлено закономірності мікроударного втомного руйнування відпалених металевих матеріалів у жорстких умовах навантаження. На підставі закону підсумовування пошкоджень та врахування особливостей утворення тріщин у динамічно деформованих об'ємах матеріалів, що зношуються, отримана модель для ерозії. Узагальнення отриманої часткової моделі на мікро-макромасштабному рівні зношування дозволило отримати універсальну статичну залежність, придатну для оцінки довговічності матеріалів. Наведено закон підсумовування пошкоджень для ступінчастого навантаження.*

***Ключові слова:** тріщина, зношування, ерозія, втомна довговічність.*

Introduction

The destruction of the volume of material on the surface of the engine cylinder liner, subjected to repeated dynamic loading by cumulative microjets , liquid drops or spherical shock waves, can be schematically represented as follows (Figure 1).

The action of a single pressure pulse on the material surface leads to the formation of a dent, on the periphery of which concentric isolated cracks of small depth appear. The occurrence of a crack is associated with the presence of surface defects such as microcracks present in a thin surface layer of the material before loading and the action of tensile stresses from Rayleigh waves. At the first stage, compressive stresses predominate in the wave passage zone. Subsequently, a shear wave separates from the contact region, and noticeable tensile stresses act at a considerable distance along the radius in the deformed zone of the material.

At some depth $\delta$from the surface, transverse cracks may occur. We can assume that the depth of their location corresponds to the boundary of the plastic deformation zone δ. The cause of transverse cracks is the so-called "internal reflections", in particular, the reflection of an elastic unloading wave from a slower longitudinal elastoplastic wave. It is important to note that the elastic unloading wave after reflection turns into a stretching wave.

Objects and methods of research

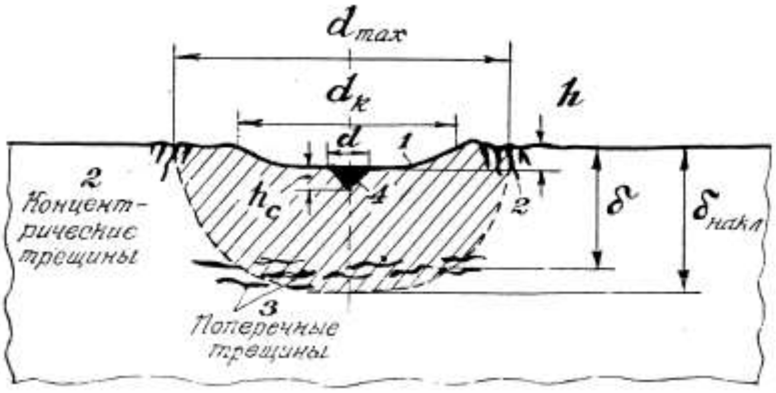
To study the fatigue life of wear materials, special samples of structural steel were modeled. Special samples subjected to cyclic world shocks.

Research method

To determine the fatigue life of wear materials, a method was used to assess the destruction from cyclic fatigue at the macroscopic level using the linear theory of damage accumulation.

Results and its discussion

According to the data of [1], on the surface of a crater, when metals are tested on MSW, conical depressions with a depth with a right angle at the top can appear $h_c \cong 0{,}1 d_k$. The occurrence of such depressions is associated with the action of the greatest shear stresses (Figure 1). It is also obvious that damage can occur in the bulk of the material under the contact patch as a result of the accumulation of shear strains along with the detachment action of the reflected unloading waves.



1 – surface of the crater; 2 – concentric cracks;
3 – transverse cracks; 4 – conical recess in the center of the crater
Fig. 1. Scheme of the location of damage when exposed on the material of the liquid jet (liquid droplets)

In some cases, the appearance and further development of radial cracks in the contact zone due to erosive chipping of more brittle components of the microstructure, for example, carbide particles in steels, cast irons, and other materials, cannot be ruled out in the contact zone.

Depending on the impact velocity and material properties, the initiation and development of cracks from the initial size ℓ_0 to the critical length ℓ_{cr}, sufficient for the subsequent formation of wear products by chipping or tearing, can occur after a different number of external pulses.

From individual strong impacts in the material, apparently, cracks of critical length and erosion products corresponding to them in size can immediately appear. The speed of such impacts will be comparable to the critical speed ϑ_{cr}, which is an important characteristic of the wear material.

If the destruction occurs after a significant number of impacts, i.e. If there is low- or high - cycle surface fatigue, then the growth of a crack to a critical length can be considered as a result of the interaction of stress waves with the tips of activated cracks. The curvature of surface cracks observed in practice during their propagation deep into the material is a consequence of such an interaction. It is important to note that a stress wave does not have to be tensile in order for a crack to grow. It was theoretically and experimentally shown in [2] that the interaction of a compression wave with a crack tip leads to the appearance of tensile stresses in the material in front of the crack and to a change in the direction of its further growth.

From the point of view of linear fracture mechanics, it can be assumed that the resistance of the material at impact velocities $\vartheta \geq \vartheta_{kp}$ is related to the fracture toughness K_{IC}; at $\vartheta < \vartheta_{cr}$ and relatively slow crack growth - with cyclic viscosity, namely: with the parameter $K_{IS}^{\min}$ characterizing the conditions of crack starting (activation) at the least constraint of plastic deformation, and with the parameter $K_{IS}^{\max}$ corresponding to the limiting state of the material at $K_{I\,C}$, or $K_{II\,C}$, or $K_{III\,C}$, depending on the initial material structure and loading regime .

For predictive estimates of the erosion resistance of structural materials and coatings, it is necessary to know the dependence of the critical number of microshocks , or the accumulation period of damage accumulation by a thin surface layer, on the velocity (pressure) of a jet or liquid droplets and the mechanical properties of wear materials.

An analysis of the kinetics of microshock fatigue fracture of annealed metallic materials under severe loading conditions makes it possible to consider the following regularities as the most probable:

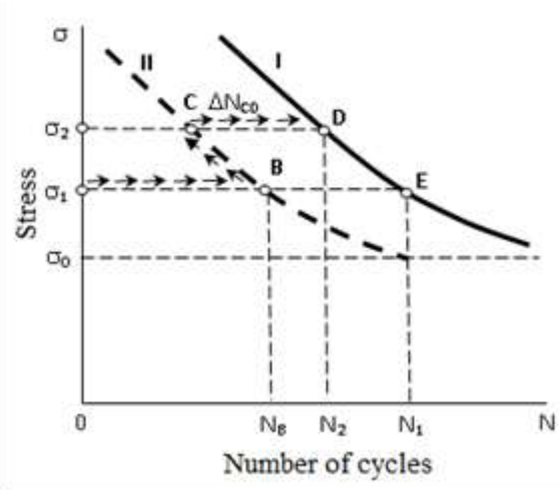
– occurrence during the accumulation period $\tau_{\text{of an accumulating}}$ plastically deformed layer with a depth $\delta_{\text{of incl.}}$;

– development of a specific microrelief on the surface in the form of ripples and separate craters of predominantly spherical shape;

– gradual destruction of the surface layer, the emergence and growth of concentric radial and transverse microcracks comparable with the dimensions of the plastically deformed layer;

– formation of erosion products comparable with the sizes of radial and transverse cracks.

When evaluating the fatigue life of wear metals, the linear theory of damage accumulation is used. A typical fatigue fracture diagram is shown in Figure 2. In this diagram σ, the stress amplitude, N is the number of cycles. We assume that the average cycle stress is zero and the stress amplitude does not change during the test.



The arrows show the transition from one load stage to another.
Fig. 2. Scheme of damage summation

In the amplitude range from σ_0 to σ_2, the fatigue curve I can be approximated by the function

$$\left(\sigma - \sigma_0\right)^n N = const_1, \qquad (1)$$

where: n and const $_1$ are experimental constants of the tested material;

n, N and const $_1$ are random variables.

Curve I corresponds to the destruction of samples from cyclic fatigue at the macroscopic level.

Curve II characterizes the moment of appearance of various damages at different load levels. The equation for this curve is:

$$\left(\sigma - \sigma_0\right)^n N = const_2 , \tag{2 }$$

where: N - is the number of loads to a given degree of damage;

$const_2$ - is a constant that characterizes the properties of the material at a given degree of damage.

For the step loading scheme shown in Figure 3, after the transition from stress σ_1 to σ_2 , the total number of cycles until the material fails will be equal to

$$N = N_B + \Delta N_{CD} . \tag{3}$$

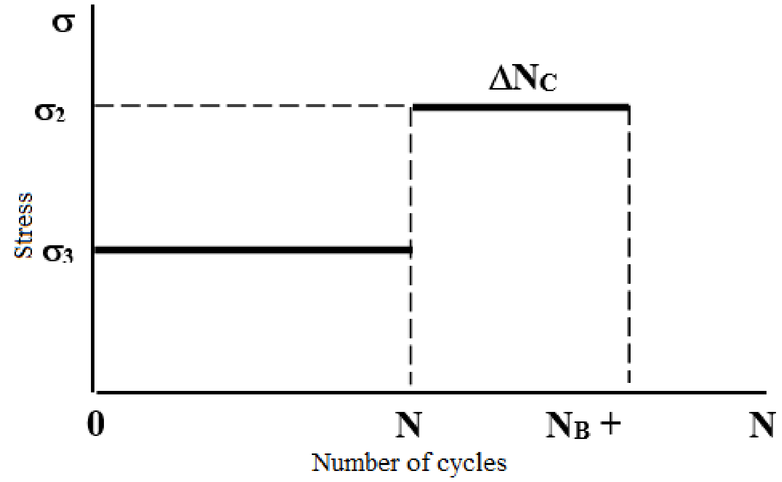


Fig. 3. Scheme of a stepped loading

Based on expressions (1) and (2) for points B , C, D and E, we can write:

$$\left.\begin{matrix} \left(\sigma_1 - \sigma_0\right)^n N_B = const_2; & \left(\sigma_2 - \sigma_0\right)^n \left(N_2 - N_{CD}\right) = const_2; \\ \left(\sigma_2 - \sigma_0\right)^n N_2 = const_1; & \left(\sigma_1 - \sigma_0\right)^n N_1 = const_1. \end{matrix}\right\} \tag{4}$$

After simple transformations of relations (3) and (4), we determine the total durability

$$N = N_2 - N_B \left[1 - \left(\frac{\sigma_1 - \sigma_0}{\sigma_2 - \sigma_0}\right)^n\right]. \tag{5}$$

From (4) the following relations follow:

$$\frac{N_B}{N_1} = \frac{const_2}{const_1} \text{ and } \frac{\Delta N_{CD}}{N_2} = \frac{const_1 - const_2}{const_1} , \tag{6}$$

from which follows

$$\frac{N_B}{N_1}+\frac{\Delta N_{CD}}{N_2}=1. \tag{7}$$

Relation (7) is a special case of the linear law of damage summation for two loading stages . In the general case, for m loading stages , the damage summation law can be written as

$$\sum_{i=1}^{m}\left(N_i / N_{\kappa p\, i}\right)=1, \tag{8}$$

where N_i is the number of loading cycles at the stress level with amplitude σ_a;

$N_{\kappa p\, i}$ is the number of loading cycles at the same level corresponding to the fatigue failure of the sample.

The right side of expression (8) when testing materials for torsion and bending can vary from 0.6 to 2.2 [3].

Returning to expression (7), we note that it contains random variables N_1, N_2 and ΔN_{CD}, which is associated with a small selection of samples with the standard method of constructing fatigue curves. To obtain deterministic fatigue properties of materials, it is necessary to increase the number of samples in a batch and apply a statistical approach when processing test results.

The refined damage summation law for the considered case of loading can be represented as follows [4]:

$$\frac{N_B}{N_{\kappa p_1}}\left[1+\frac{\left\langle\left(N_1-N_{\kappa p_1}\right)^2\right\rangle}{N_{\kappa p_1}^2}\right]+\frac{\Delta N_{CD}}{N_{\kappa p_2}}\left[1+\frac{\left\langle\left(N_2-N_{\kappa p_2}\right)^2\right\rangle}{N_{\kappa p_2}^2}\right]=1\cdot \tag{9}$$

In this form, the damage summation law makes it possible to more accurately determine the total durability under stepped loading in comparison with the linear law (7) and (8).

Conclusions

When evaluating the fatigue life of wear metals, the linear theory of damage accumulation is used. According to the fatigue fracture diagram, curves were obtained corresponding to the destruction of samples from cyclic fatigue at the macroscopic level, which characterizes the moment of occurrence of various damages at different load levels. By testing steel materials for torsion and bending, their endurance limit is determined.

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