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Thermo-kinetic model for assessment of durability of contact surfaces under lubricating.

A phenomenological model for assessing the durability of the wear layer is suggested. The model considers two areas of damage accumulation, namely the areas of multiple-cycle contact fatigue and debris layer. In the model, the methods of evaluating the parameters to describe durability cycle fatigue are suggested.

Introduction. Thermofluctuational theory of strength with regard to the destruction of the wear surfaces was developed in works [1-3], which proofed, that the equation S.N. Zhurkov was suitable for evaluation of the longevity of materials under various mechanisms of damage and types of stress-strain state of materials, as well as for evaluation of the wear resistance of surface layers, taking into account the specificity of their functioning. However, the problem of analyzing the strength and durability of a surface layer material, deformed by friction, is rather difficult task, since the study of the activation characteristics of the destruction of surface layers due to friction is complicated by the influence of numbers of concurrent and competing processes on their durability. Changes in the surface layer, that occur directly in the friction process due to the mechanical and physicochemical interaction of the contacting surfaces (deformation, texturing of the material, changing the elemental composition, chemical modification, changing various physical characteristics) lead to a significant difference of the activation energy of the destruction of the material in the surface layer and in volume. Therefore, the parameters, which characterize the debris layer change and the contact fatigue areas will be different, and their evaluation must be carried out taking into account the peculiarities of the accumulation of triborases in all areas.

The aim of the work is to develop the thermo-kinetic model of estimating the durability of contact surfaces that takes into account the influence of tribotechnical factors on the activation energy of the leading destruction mechanism during the friction in rolling and slipping conditions.

Modeling of the durability evaluation of friction pairs in the area of multi-cycle contact fatigue.

In order to construct a calculated durability evaluation by the wear criteria, as a base model we use the most well-known and widely recognized kinetic model of material destruction, based on the developed thermofluctuation concept of the strength of solids by S.N. Zhurkov [1, 2].

The durability equation (that came from this model) (1) is widely used in the modern theory of the strength of solids:

$$\tau = \tau_0 \exp\left(\frac{U_0 - \gamma\sigma}{kT}\right), \qquad (1)$$

where τ – durability of the material under load σ; τ_0– time constant equal to the period of atomic vibrations in the body $10^{-13}...10^{-12}$ c; k – Boltzmann's constant; T – absolute temperature, К; U_0 – fracture activation energy, kJ / mol; γ– structurally-sensitive coefficient.

The suggested evaluation model takes into account the presence of two areas of damage accumulation and the difference of their mechanisms of prevailing type of destruction. Thus, in the general form, the wearing layer durability can be expressed as:

$$\tau = \tau_d + \tau_\sigma \ , \qquad (2)$$

where τ_d – durability of the debris layer; τ_σ – durability of the area of multi-cycle contact fatigue.

During the research of the activation characteristics, their dependence on the stress-strain state scheme (created during tests) was established. In friction process, a complex stress-strain state of the surface layer material is created under the action of normal and tangential loads, elastic and plastic deformations, contacting bodies.

The activation energy U_0 and γ coefficient depend on the existing damage mechanism and it must be taken into account during their evaluation. The proposed model introduce a parameter ΔG , which characterizes the influence of the external environment on the energy barrier overcoming ($\Delta G < 0$- the external medium softens the destructible layer, $\Delta G > 0$- strengthens, and $\Delta G = 0$ - has a neutral effect).

In the submitted study the activation parameters of the field of multi-cycle fatigue are considered.

Imagine an expression that determines the durability of the area of multi-cyclic fatigue, in the form:

$$\tau_\sigma = \tau_0 \exp\left(\frac{U_{0_\sigma} - \gamma_\sigma \sigma_\sigma \pm \Delta G_\sigma}{kT_\sigma}\right). \qquad (3)$$

Taking into account the cyclicity of the loading process, we will present the operating time τ_σ via the number of cycles N and the actual loading time per cycle $t_ц$:

$$\sigma_\sigma = \frac{U_{0_\sigma} - RT_\sigma ln\left(\frac{N \cdot t_ц}{\tau_0}\right) \pm \Delta G_\sigma}{\gamma_\sigma}. \qquad (4)$$

In the work [4], an accuracy increase of evaluating the stress state of a surface layer during friction is achieved by analyzing the equivalent stresses $\sigma_{экв}$, which takes into account the simultaneous action of compressive and shearing loads on the contact surfaces.

Assume that:

$$\tau_{max} = 0{,}304\sigma_{max} \ , \qquad (5)$$

where σ_{max} – maximum contact pressure for Hertz, τ_{max} – maximum tangential stresses. As a result, the equivalent stresses in the contact, according to [5], are:

$$\sigma_{экв} = \sqrt{\sigma_{max}^2 + 3\tau_{max}^2} \qquad (6)$$

Thereby, taking into account the above analysis of the stress-strain state of the contact surfaces, the kinetics of the accumulation of activation energy of destruction under rolling and slipping conditions, the equation (3) will have next form:

$$\tau_\sigma = \tau_0 \exp\left(\frac{U_{0_\sigma} - \gamma_\sigma \sigma_{экв} \pm \Delta G_\sigma}{R T_\sigma}\right). \qquad (7)$$

Methods to evaluate the value of activation energy of destruction under dynamic loading conditions.

Methods to evaluate the value of activation energy of the leading destruction mechanism consist of the following:

- tests of material samples are conducted with the help of an automated tribological complex, the main characteristics of which are described in [6], in a selected range of loads at the contact pressure of Hertz (100 - 500 MPa) in a rolling manner with a different degree of slipping (3 to 40%);
- tests in non-stationary mode (acceleration – stationary operation - braking – stop) are conducted according to the following scheme: running-in in the lubricant environment and subsequent operating until stabilization of the main tribotechnical parameters of contact;
- create the conditions for stopping the supply of lubricant to the friction zone and fix changes of the main tribotechnical parameters of the contact till first signs of contact surfaces setting;
- determine the durability of tribocoupling $\tau_{p\sigma} = N t_{ц}$ by the operability of friction pairs for a number of temperatures and loads;
- calculate the critical temperature in the contact zone of the tribo-conjugate elements, which is expressed by the dependence: $T_\sigma = t_0 + \vartheta$, where t_0 is the temperature of the surfaces before entering the contact zone, ϑ is the flash point by Block, which represents the instantaneous increase of temperature when the jamming occurs.

It is possible to determine the activation energy of destruction on the base of obtained experimental data of changing $\tau_{p\sigma}$ and T_σ, depending on the contact pressure, with the help of formula:

$$U_\sigma = R T_\sigma ln \frac{\tau_p}{\tau_0}. \qquad (8)$$

The results of experimental research to determine the activation characteristics of the fatigue mechanism of destruction of tribocomplement elements.

As an example, we present the obtained results of the activation energy of destruction of steel 45 (HRC 38) under the friction in non-stationary conditions in the TAD17-i transmission oil environment (SAE 80w90 API GL-5) under rolling conditions with varying degrees of slipping (3 to 40%) (table 1).

Table 1.

Experimentally-calculated parameters during determining the activation energy of destruction of steel 45 under non-stationary conditions of friction

Parameters	Degree of slip in contact in rolling and sliding conditions, %				
	3	10	20	30	40
	$\sigma_{max} = 170MP$a, ($\sigma_{экв} = 192MP$a)				
τ_{p170}, c	27000	23000	20000	18000	15600
T_{170}, K	293,5	313	384	461	635
U_{170}, kJ / mol	97	103	127,01	150,96	209
τ_{p250}, c	$\sigma_{max} = 250MP$a, ($\sigma_{экв} = 279{,}38MP$a)				
	21000	18000	14700	12900	11500
T_{250}, K	299	323	415	506	703
U_{250}, kJ / mol	99,15	106,69	136,39	165,75	229,6
	$\sigma_{max} = 300MP$a, ($\sigma_{экв} = 338{,}1MP$a)				
τ_{p300}, c	18000	15000	12450	9000	7000
T_{300}, K	315	343	438	541	755
U_{300}, kJ / mol	104,05	112,78	143,34	175,59	243,47

According to the obtained dependencies $\tau_p(\sigma)\sim f(\sigma)$, the limiting value of the contact pressure $\sigma_{пред}$ is determined by extrapolation, and the activation energy of destruction $U_{0\sigma}$ is determined by extrapolating the value $U(\sigma)$ from the dependencies $U(\sigma)\sim f(\sigma)$ to the established maximum value of the contact pressure $\sigma_{пред}$.

Thereby, $\sigma_{\sigma_{пред}}$ can be interpreted as the limit of fatigue strength under N loading cycles.

We determined the effective characteristics of the stress-strain state of the subsurface layer of the particular part (by the method of finite or boundary elements). Also we have the activation characteristics of the fatigue destruction mechanism U_{0_σ}, γ_σ, ΔG_σ, which allow to take into account the influence of physical aspects on the fatigue damage accumulation process. These aspects do not have significant impact on the stress-strain state of subsurface layer, but are significant factors in determining the mechanism of formation, the rate of accumulation and development of fatigue damage in conditions of tribo-contact interaction.

The presented kinetic model reflects an increase of the internal energy of the material in the process of nonstationary cyclic loading. Increasing the rate of slipping in rolling with sliding increases the level of accumulation of the activation energy of the leading destruction mechanism. Firstly it is connected with an increase of the plastic deformation rate, an increase of the temperature and gradient of the shear rate in the contact due to an increase in the sliding speed from 0.062 to 1.15 m / s with slipping from 3 to 40%, respectively.

Conclusions

1. A technique for estimating the activation energy under dynamic loading conditions is developed and the possibility of predicting the life of tribo-conjugate elements in the kinetics of the accumulation of activation energy of destruction under the friction is presented.
2. The influence of the rate of slipping in rolling with sliding, the local temperature increase in the contact, the stress-strain state on the level of accumulation of the activation energy of destruction for steel 45 while lubricating with gear oil is established.

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