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Synergetics Principles of the Regularity of the Development of Microcracks in Elements of the Friction Units

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Abstract

In the study of tribological processes the highly nonequilibrium states of crystal lattice arise inside the frictional contact. It is no longer described by Hooke's law, and undergoes a local structural transformation, besides its movement toward the equilibrium occurs as a synergetic process. However, the application of purely synergetics within the framework of continuum mechanics, by itself leads to the conflicting conclusions.

The synergetic principles and the fractal approach of physical mesomechanics allow to describe kinetics of the plastic deformation and fatigue of various materials under different loading conditions from a single point of view, including the cyclic loading of tribocoupling, controlling of points of the bifurcation.

In this paper, the stress-strain state of brake disks of transportation vehicles is analyzed to prevent the occurrence of microcracks on their working surfaces and the model is developed for studying nonstationary friction modes and fracture of contacting elements. The concept of metal fatigue is developed within the framework of physical mesomechanics.

The proposed model explains the change in the mechanism of crack propagation under conditions of low-cycle fatigue of metal-polymer friction pairs when air enters the crack, and leads to the oxidation of fracture surfaces with the formation of a film. Perhaps, in this case, the formation of surfaces with a subgrain structure occurs.

Keywords: friction device, synergetic principles, metal-polymer friction pair, low-cycle fatigue, mesomechanics, microcrack.

Introduction

In the study of tribological processes the highly nonequilibrium states of crystal lattice arise inside the frictional contact. It is no longer described by Hooke's law, and undergoes a local structural transformation, besides its movement toward the equilibrium occurs as a synergetic process. However, the application of purely synergetics within the framework of continuum mechanics, or the theory of dislocation by itself leads to the conflicting conclusions.

In recent years, views on the nature of plastic deformation and fracture have changed significantly, and there has been a shift from traditional concepts of the dislocation theory. By introducing the concept of the structural levels of deformation, the structurally unstable states, the dissipative structures; the plastic deformation is viewed from the prospect of the hierarchy of structural levels of deformation; and the destruction of a solid body is considered as a special case of the emergence of dissipative structure at a high structural level [1 – 3].

The synergetic principles and the fractal approach of physical mesomechanics allow to describe kinetics of the plastic deformation and fatigue of various materials under different loading conditions from a single point of view, controlling of points of the bifurcation, including the cyclic loading of tribocoupling.

Synergetics, in contrast to the classical thermodynamics, reflects on the kinetics of entropy and gives it, rather than energy, a decisive role in the formation of the properties of an open system that exchanges energy and substance with the environment [4]. Studying the behavior of the system at the points corresponding to the spontaneous self-organization of the dissipative structures – bifurcation points – is important for the theory of mechanical properties of materials. Since fracture is an irreversible process, it should be evaluated from the view of the system behavior being far from thermodynamic equilibrium [2].

The idea of relationship between the period of crack development and the durability of material in different areas of high- and low-cycle fatigue can be obtained by examining in more detail the fatigue fracture curve of materials by stages of the damage accumulation.

During the cyclic loading, at a constant level of the alternating stress, the process of accumulation of irreversible damage occurs initially in the material, and when a certain critical level of the defect density is reached, the initial crack surface or the fracturing zone epicenter appears (Fig.1) [4].

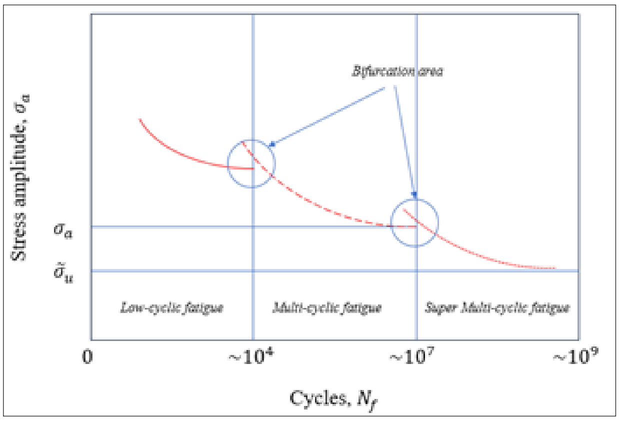

Figure 1: Multi-mode model of the complete fatigue life of materials with the bifurcation regions

As it can be seen from the diagram of cyclic fatigue of materials (Fig.1), the break of fatigue curves is observed in the region of transition from the low-cycle to high-cycle fatigue, which is associated with a change in the fracture mechanism. The existing obvious experimental data suggests that in case of a change in the alternating stress, any metal behaves in such way that when upon reaching at least two critical stress levels a self-organization change takes place in the leading fracture mechanism. This is a typical situation for the evolution of open or partially closed synergetic systems, which should be considered from the standpoint of the physical mesomechanics of destruction [4].

The revealed features of the destruction of materials under such conditions of cyclic loading allowed us to distinguish a new range of super-multi-cycle-fatigue (SMCF) – 107-109. The transition from one fatigue regime to another occurs within the transit area called the bifurcation area [5]. Currently, there is no standardized system for determining the boundaries of the bifurcation area. Using the established over decades the views of many authors, who are still unify the low-cycle-fatigue [LCF] – 10^4, and the multi-cycle-fatigue [MCF] – 10^4-10^7 into a single classic Wohler curve of fatigue, S-N curve.

With the further decrease in the level of external load, the next bifurcation area appears associated with a change in the failure mechanisms from MCF to SMCF (Fig. 1).

In regions where the mechanism of fracturing changes, a significant scatter of experimental data with respect to a number of cycles is possible, and these changes are of the possible nature. Moreover, an analysis of the experimental fatigue curves shows that the nature of a decrease in the cyclic strength while increasing the loading cycle turns out to be similar for LCF, MCF and SMCF branches, which allows us to formulate a hypothesis about the similarity of their mathematical description.

In this paper, the stress-strain state of brake disks of transportation vehicles is analyzed to prevent the occurrence of microcracks on their working surfaces and the model is developed for studying nonstationary friction modes and fracture of contacting elements. The concept of metal fatigue is developed within the framework of physical mesomechanics.

The conditions of thermal equilibrium are studied under the balanced heat dissipation and the heat removal, when the heat released during the reaction is completely removed through the surface of contact spots of microprotrusions of polymer lining.

Purpose of Work

To evaluate the stress-strain state of the brake discs of transportation vehicles to prevent the occurrence of microcracks on their working surfaces and to develop a model for studying nonstationary friction modes and fracture of contacting elements.

Problem Statement:

Due to significant temperature stresses resulting from the action of high temperatures, the microcracks appear on the friction surface of disk, accelerating its failure. The formation of large temperature stresses is also facilitated by anisotropy of the material properties and the difference in thermophysical and mechanical characteristics of the structural components of the friction unit (linear expansion coefficient, thermal conductivity, elastic modulus). The existing COSMOSWorks program in the SolidWorks environment [6] allows one to perform thermal calculation with complex heat transfer (convective, conductive, and radiation) to determine the surface temperature gradient and the temperature stress-strain state of the surfaces under study. The disadvantages of the program include the fact that it immediately sets the coefficient of heat transfer through the product layers without taking into account the heat transfer coefficients to the air washing them, in addition, it is impossible to determine the high temperature gradient of the product in it.

Solution of problem. In the braking process of vehicle as a result of the friction forces arising from the frictional interaction of the working surfaces of the pads and the disk, their friction surfaces are heated to high temperatures, approximately 800°C. An increase in the surface temperature gradients of the disk leads to its axial distortion. Temperature deformations at the junctions of the non-working surfaces of the disks with the ribs forming the ventilation ducts cause a waviness or sinking of the friction surface of the disk, which increases the specific loads in the friction pairs and leads to the appearance of local thermal spots on the friction surfaces of the disk. This leads to a deterioration in the wear-friction properties and the strength bond of the formations resulting from structural transformations. With prolonged action of surface and deep temperature gradients in self-ventilated disks, microcracks arise and develop, with cracks reaching the outer surface of the friction belts of the disks. Analysis of the stress distribution showed that thermal and mechanical stresses on the structural elements of the friction pairs are distributed unevenly, and over a very wide range - from 20 to 370 MPa.

Numerous studies [6, 7, 8, etc.] of the high-strength steel have shown that a decrease in the region of safe states observed with the increasing temperature is accompanied by some change in the shape of limiting curves. The most noticeable reduction in areas corresponding to lower tolerances for permanent deformation. Moreover, with increasing temperature, the experimental points move inside the Mises ellipse closer to the Coulomb rectangle.

A duration of the operational cycle of a vehicle's disc-shoe braking unit is determined by the allowable wear of the friction linings, and the responsibility for the occurrence and development of foci of microcracks on the friction surface of the disk lies mainly with its stressed and deformed state [9].

A visual inspection of the surface of the friction pairs showed that the brake discs had local sections of microcracks located on their friction surfaces (Fig. 2 a, b, c, d), where the destruction occurred along planes perpendicular to the direction of maximum stresses. It is known that the formation process and the type of area with microcracks are largely determined by the amount of energy accumulated in the surface layer of the disk friction belt. The type of fracture — by shear, normal and temperature stresses — is determined by the propagation velocity of microcracks along sections of the friction racetrack [10].

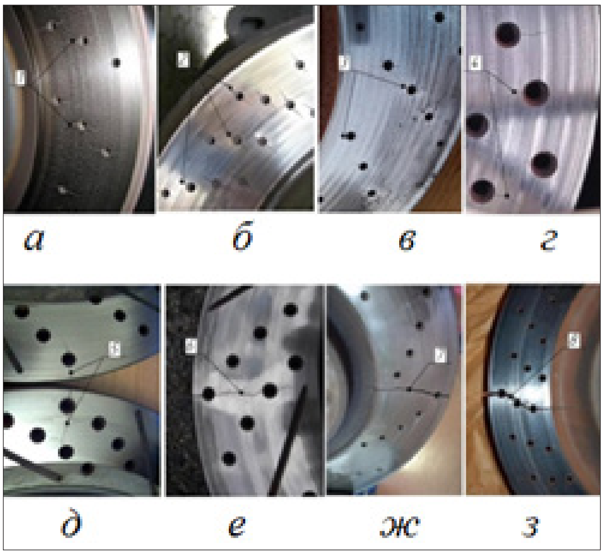

Figure 2: a, b, c, d, e, f, g, h - Foci of microcracks when the holes are located at an angle (a, b, c) and a fan (d), as well as combined variants (holes with grooves) (e, f) made in the brake discs and cracks on their surfaces (f, g, h): 1, 2, 3, 4, 5, 6, 7, 8 - local microcracks and cracks on the surface of the disc

In case of the electro-thermomechanical friction in a disk-shoe brake, the occurrence and development of microcracks occurs on the working surface of the disk friction belt, and destruction occurs along its generatrix. A thorough inspection of the brake discs (see Fig.2 e, f, g, h) with the cracks formed showed that in the entire range of surface and volume gradients the fracture temperatures occurred due to shear due to friction and made an angle of about 45° with the plane tangent to the surface of the disc.

Cracking of friction surfaces as a result of thermal action is also observed on the bandages of railway wheels, cast iron and steel, respectively, drum and disc brakes of vehicles.

Significant powers are absorbed in the friction devices, increasing with increasing vehicle speed and mass. The requirement to have a shorter braking distance determines a short braking time and very intense heating of surfaces with the formation of large thermal stresses. As a result, cracks may appear on the friction surfaces. On drums and disks of vehicles, cracks are located almost regularly across their friction racetracks (Fig.2 f, g, h).

Let us analyze the macrocracks presented in Fig. 2 a, b, c, d, which are subject to the brake disks of the vehicle due to the bilateral heating of their friction belts:

- through holes are concentrators of mechanical stresses, on which temperature stresses are caused by high surface temperature gradients;
- grooves at an angle on the surfaces of the brake disk, the depth of which is 0.1–0.12 of its thickness, allows them to act as compensators for the effect of the expansion of the body of the disk when it is heated.

With one-sided heating of a metal friction element, previously unknown patterns of the occurrence and development of microcracks on its working surfaces are established in the presence of stress stress concentrators taking into account thermal stresses. The latter arise due to the action of high temperature gradients during electro-thermomechanical friction of microprotrusions of metal-polymer pairs under the influence of mechanical, electrical and thermal fields of a pulsed nature. In the surface layer, thin films of secondary structures are destroyed. Surfaces in this case are subject to mechanical and thermal distortions at high waves of current stresses, which include constant mechanical and residual thermal stresses. The mechanisms of electronic and ionic thermal polarization of various intensities, weakening the surface layer, operate here. At the same time, alternating high temperature gradients are formed on the surface and in the subsurface layers of the friction metal element along its length and thickness, contributing to the aperiodic cyclic processes "expansion (heating) - compression (cooling)". These processes cause a violation of thermodynamic stability and, as a result, the formation of a network of microcracks in the form of a fractal structure. The metal under load cannot be in a thermodynamically stable state, and the resulting discontinuities are filled with elements of the metal itself or with residual gases diffusing in the crack region. In the zones of crack initiation, where the Gibbs thermodynamic potential becomes greater than zero, the crystal cannot exist thermodynamically stable.

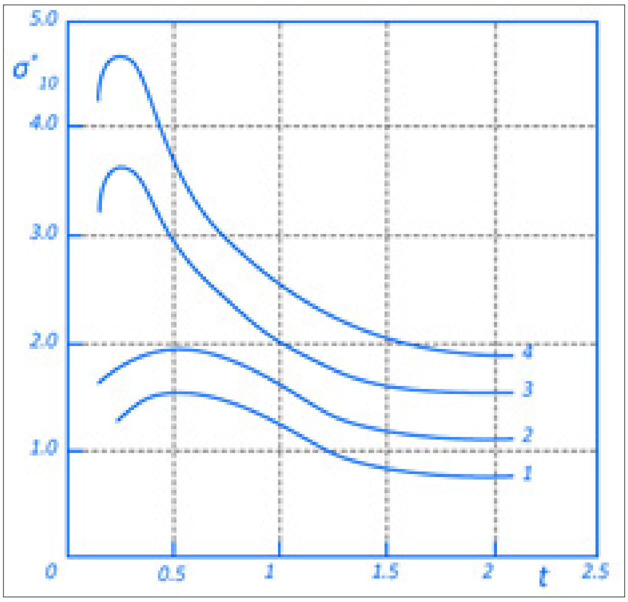

Figure 3: Dependence of dimensionless stress on dimensionless braking time during pulley cooling for various values of the Biot criterion:
1 – Bi = 0.5; 2 – 1.0; 3 – 5.0; 4 – ∞, x = 0

To analyze the thermal and mechanical effects on the surface and subsurface layer of the material of the friction element, we proposed the thermomechanical theory of friction [11], a model based on which we studied the non-stationary modes of wear and fracture of contacting parts in braking mode. It is proved that the main part of the stresses arising during friction is concentrated in the surface layers of friction elements. These stresses become proportional to the flash point and cause strong heating in thin surface layers, which leads to the formation of burns, thermal spots and foci of microcracks.

Therefore, we can assume that it is in the near-surface layer in the case of heating when exposed to a temperature flash T_fl that the cracks arise due to the thermal fatigue of the material. These cracks are further developed as a result of cooling of the layer surfaces and the appearance of a temperature gradient when thermal stresses in the surface layer reach the highest values determined by formula (1) and pass through a maximum (Fig.3) [11]:

$$\bar{\sigma}^*_{10} = \frac{kBi}{kBi + \frac{1}{\sqrt{\pi \bar{t}}}}\left[\frac{2}{\sqrt{\pi}}\left(1 - e^{-\frac{1}{4\bar{t}}}\right) + erf\left(\frac{1}{2\sqrt{E}}\right)\right],$$

where k – the overlap coefficient, $Bi = \frac{\sigma' b}{\lambda}$ – the Biot criterion, $\bar{t} = \frac{at}{b^2} = Fo$ –the dimensionless time, or the Fourier criterion, $\bar{x} = \frac{x}{b}$ – the dimensionless spatial variable, b – the effective depth of heat penetration, σ^1 – the heat transfer coefficient, E is the elastic modulus of the material, λ – the heat conductivity coefficient, *a* – the coefficient in the heat equation $\frac{\partial T}{\partial t} = a\frac{\partial^2 \Delta T}{\partial x^2}$; $\Delta T(x,t)$ – the temperature difference,

$$\mathrm{erf}(x) = \frac{2}{\sqrt{\pi}}\int_0^x e^{-t^2}dt = \Phi\left(x\sqrt{2}\right),$$

Φ(x) – the standard normal distribution of the random variable.

An analysis of the wear mechanism of friction pairs showed that under conditions of low-cyclic heating and cooling, both the multiphase structure and the thermal properties of individual phases have a great influence on the nucleation and development of cracks. A certain role in the destruction of the material is played by the nature of the distribution of cracks on the surface.

Since the flash point can quickly reach several hundred degrees, such a jump in temperature can lead the material to a plasticity state when the friction resistance decreases. Since the duration of interaction on the spots of actual contact is 10^{-6}-10^{-3}s, it is important not the properties of the static strength of the surface layer of the material of the friction pair, but the properties of fatigue strength, given that the crystal lattice of a solid responds to impacts after 10^{-8}-10^{-5}s. Therefore, the adjustment of the surface layer under the influence of external thermal loads occurs precisely in the process of establishing the temperature field, and by the time the steady-state temperature is reached, the surface layer is already under the influence of various residual stresses.

The calculations showed that the speed of the thermal process has a significant effect on the main indicators of the quality of the surface layer. The speed of thermomechanical processes leads to a significant change in the nature of structural transformations in the surface and near-surface layers, as well as the physical and mechanical properties of the material. In the process of friction, the zone of plastic deformation is not limited by the volume of irregularities but extends deep into the material. Moreover, the material of the surface and subsurface layers has a low dislocation density. When sliding, dislocations accumulate at a certain distance from the surface, their density increases, which leads to the formation of micro-voids in the subsurface layer [12].

The depth of heating of the surface layers is significantly affected by cooling (the Biot criterion). With the same parameters of the heat source, the maximum depth of heating of the surface layer to a given temperature during cooling is always less than without cooling. The presence of heat transfer increases the cooling rate of the surface of the material, but with the distance from the damage the influence of cooling decreases. This is especially important for intermittent brakes. Since the temperature-force effect affects the nature of the change in the heating and cooling rates and the temperatures at various depths of the surface layer, this can be used to study the effect of cooling conditions on the kinetics of the thermal process.

The development of ideas about metal fatigue in the framework of physical mesomechanics is associated with an intensive study of the accumulation of damage in them, primarily in the field of multi-cycle fatigue, which led to the understanding that low-cycle fatigue should correspond to a higher scale level of accumulation in metal [13].

It is quite natural to expect that at the transition from one scale level to another there should be a change in the way energy is absorbed by the metal. It manifests itself due to the difference in the self-organized inclusion of metal in the process of damage accumulation of new evolutionary mechanisms that could not be realized at the previous scale level.

The reason is the fact that the metal behaves as a complex, hierarchically ordered system. The indicated transition to a different behavior of the metal at a new scale level is reflected in the fatigue curve by a certain feature that changes the law used to describe the process of its evolution [2].

The surface layer, as the main energy accumulator during the initiation of cracks on the surface, is an independent subsystem of the metal, while the metal behaves as a complex, hierarchically ordered system. It is precisely its role in crack initiation that determines the durability for the entire cross section at a given level of stress. Of course, the structure of the material determines the structure of the surface layer, but it is the friction surface under external influence, as well as the interaction with the environment that accumulate the flow of dislocations, the cascade of slip bands, which, when a certain density is reached on the friction surface, create conditions for the occurrence of friction under the surface [11].

When the critical surface curvature, critical density of dislocations and slip bands of their maximum saturation by gases from the environment are reached, intense heat exchange with the environment occurs, which reflects synergetics in achieving the ultimate state of the material in the surface layer. In addition, there is a mechanical interaction on the spots of actual contact, leading to a concentration of stresses, and the crack receives an equally probable possibility of occurrence on the surface of friction and under the surface.

Thus, the behavior of a metal in a wide range of amplitudes of variable cyclic loads (external, thermal, and others) is characterized by a bifurcation fatigue diagram that describes the behavior of a metal at three scale levels based on approaches of physical mesomechanics and takes into account the existence of bifurcation transitions from one scale level to another.

The model of mechanical action on the surface of a material considered in [11] suggests that the same processes occur in a surface layer during friction as under impact. In the dynamic theory of crystalline media with dislocations, it is shown that, along with the well-known types of waves (elastic precursor, volume elastic compression wave) and viscous flow, a strongly dissipative wave of plastic rotations damped in a thin surface layer is initiated along with well-known wave types. This should lead to the formation of a layer with strong crystallographic misorientations near the impact surface, and, consequently, with a high dislocation density, since the presence of a crystallographic rotation gradient leads to the appearance of a dislocation density. Such layers with a high dislocation density are indeed observed in experiments on the shock stress of materials [13].

Conclusion

A model of non-stationary modes of friction and destruction of contacting elements has been developed, which has shown that thermal explosions are the most characteristic during frictional interaction in metal-polymer friction pairs, in which, at the first stage, the internal chemical energy of the subsurface layer of the polymer lining is converted into heat. Moreover, this layer has a small heat release, due to the short time of chemical transformation, which occurs without the participation of oxygen.

It is shown that during the development of a crack below the surface, its growth at the first stage occurs at a lower rate, in comparison with the crack growth rate with atmospheric access.

The proposed model explains the change in the mechanism of crack propagation under conditions of low-cycle fatigue of metal-polymer friction pairs when air enters the crack, and leads to the oxidation of fracture surfaces with the formation of a film. Perhaps, in this case, the formation of surfaces with a subgrain structure occurs.

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