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PECULIARITIES OF WEAR OF THE WORKING SURFACES OF PARTS OF SHIP'S TECHNICAL EQUIPMENT (STE)

Statement of the problem in general. The energy load of the contacting surfaces plays a significant role in the working units of parts of the STE. It largely depends on the speed of its movement and mass during long-term or cyclic loading of the working steam. At a high level of energy consumption, a decrease in the braking torque of sliding bearings is observed due to a drop in the dynamic coefficient of friction due to an increase in temperature on the working surfaces of the contacting elements. If the temperature of the friction surfaces exceeds the allowable one for the materials of the working pair, a decrease in braking efficiency is observed, and intensive wear of the working surfaces and their destruction occurs. At the same time, due to high temperature gradients on the surface of the metal friction element, high temperature stresses develop, which contribute to the initiation and development of microcracks, which leads to its destruction.

Analysis of recent researches and publications. Loading on the couplings of STE parts, in particular, on the crankshaft of a piston engine under operating conditions is random, since most of the time the engines are operated in unstable modes. In addition, the fatigue resistance characteristics of the materials from which the crankshafts are made are also random values. Therefore, the interpretation of strength conditions should be based on probabilistic concepts [1].

Most of the structural elements of the ship work under conditions of cyclic loading, which creates favorable conditions for the development of fatigue cracks.

The analysis of the results of the destruction of STE parts using the example of crankshafts in operating conditions indicates that the largest number of them occurs on the cheek with the initiation of a fatigue crack in the connecting rod of the connecting rod neck and the cheek in the plane of the crank. The main cause of such breakdowns is a high stress concentration in the bars.

Formulation of the problem. Is to improve the performance of the operating parameters of the contacting nodes of the STE parts with the application at the stage of their design of the results of a system approach to research on changes in the operating characteristics of the tribosystem.

Presentation of the main research material. A large number of factors affecting the onset of local destruction of the materials of the contact spots of the microprotrusions of the friction pairs due to thermal fatigue does not allow the development of a universal experimental technique, the results of which would be adequate to the phenomena that take place in real conditions. When analyzing the load conditions of the contacting steam, the thermal conditions of its operation should be subjected to a careful assessment: the nature of the change in the temperature gradient along the surface and in the cross-section of the near-surface layer, the intensity of heat transfer, the amount of thermal expansion, as well as the duration of thermal loads and their cyclicity.

Currently, thermal fatigue is described as a process of deformation and formation and increase of structural damage of microprotrusions of contact spots of friction surfaces under the influence of multiple changes of pulsed thermal currents. At the same time, they mean that thermal fatigue affects all load processes (mechanical, electrical, electromagnetic, and chemical), during which cyclical changes in pulsed electric currents should occur.

In real conditions, the microprotrusions of the working surfaces of pairs of joints during electrothermomechanical friction can be subjected to the following thermal loads: shock pulse heating and slow forced cooling; heating and forced cooling at high rates; slow heating and intense forced cooling; heating and cooling at low rates. In the conditions of cyclic heating and forced cooling, the multiphase structure and thermal properties of individual phases have a significant impact on the nucleation and development of cracks. A certain role is played by non-metallic inclusions (wear products of friction materials), which, accumulating in the cracks formed on the surface of the counterbody, work as a wedge (Fig. 1). A network of microcracks appears on the friction surface. During braking of the coupling parts, the sharp edges of some microcracks have a cutting effect, other microcracks are filled with wear products of the friction material and oxides formed as a result of gas corrosion of the friction surface. These inclusions can be one of the main reasons for the development of cracks if they have a striated arrangement.

Figure 1 - The nature of the initiation and development of cracks along the width of the joint

When considering the kinetics of fatigue crack growth according to V.S. Ivanova, it is important to identify areas of change in crack length, within which the same micromechanism (normal separation, transverse or longitudinal microshear) controlling the crack growth rate is preserved.

The entire process of fatigue failure of carbon steels can be divided into several stages:

$$N_p = N_j + N_{jj} + N_{jjj} + N_{jy},$$

where NP - overall durability of the structural element; Nj - the number of cycles corresponding to the initiation of microcracks and their growth within one grain of the microstructure; Njj - число cycles corresponding to the development of a crack from the size corresponding to the grain diameter to the appearance of a macrocrack; Njjj - the number of cycles corresponding to the development of a macrocrack; Njy - the number of cycles corresponding to the doloma process.

The areas of self-similar crack growth correspond to certain critical crack lengths, within which the activation energy of the process controlling the crack growth rate does not depend on the crack length, i.e., the same mechanism of destruction is preserved. In general, the fatigue process according to the fatigue failure diagram has several stages (Fig. 2).

Based on the analysis of experimental fatigue kinetic diagrams of structural materials, it is shown that the following growth rates are realized for different stages of fatigue microcrack development: I - the stage of slow crack growth, the growth rate does not exceed 10-5...5·10-6 mm/cycle; II - the stage of stable growth of cracks at velocities varying in the range of 10-5...5·10-6< and <10-3 mm/cycle; III - the stage of unstable growth of cracks at velocities and >10-3 mm/cycle.

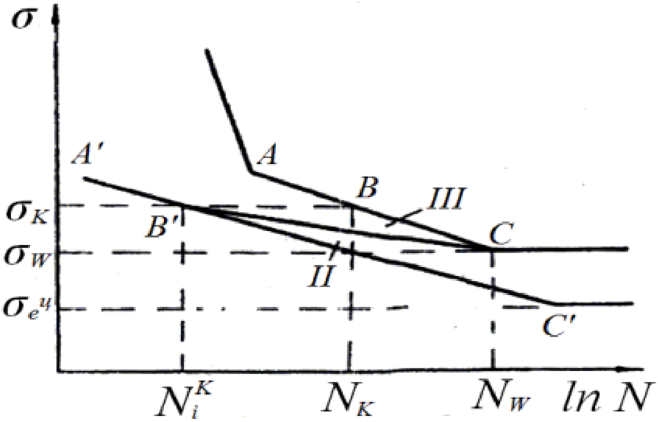

Figure 2 - Fatigue failure diagram according to V. S. Ivanova;
σ_W - the limit of fatigue; σ_K - critical fatigue stress; $\sigma_a^{ч}$ - cyclic limit of elasticity.

The nature of the thermal load distribution is influenced by the state of the surface layer, its microstructure, change in hardness, roughness, waviness of the surface, etc. Attention should be paid to the appearance of wrinkles on the surface of the metal element and a network of cracks on the surface of the contacting materials after cyclic heating and forced cooling. As V. S. Ivanova's research showed, heating and forced cooling at high rates lead to a change in volume and are accompanied by a martensitic transformation of the steel structure of the counterbody.

The II stage of established destruction is characteristic of the above-mentioned process, here there is a transverse microdisplacement of the microprotrusions of the contacting surfaces.

The results of studies of the process of wear and damage of working pairs during electrothermomechanical friction made it possible to establish that the type of destruction of contact surfaces is determined by the level of thermal load, external mechanical, electrical, electromagnetic and chemical influences on the surface of the contact spots of microprotrusions, high-speed flows of the components of the washing medium and the properties of the surface layers of materials that rub.

The main part of the thermal stresses arising during friction is concentrated in the subsurface layers of the metal friction elements, which is confirmed by the known analytical relationship between the braking time n and the effective depth of heat penetration $b = 1,73\sqrt{at}$ (where a is the coefficient of thermal conductivity of the material of the periphery of the connection). On the spots of actual contact, as shown by A. Kh. Dzhanakhmedov, G. A. Fazekas, A. V. Chichinadze, V. Cherpel, F. Piggel, etc., these stresses become proportional to the flash temperature, this is accompanied by strong heating of the near-surface layers, which leads to the formation of burns, thermal spots and nucleation centers and the development of microcracks.

Therefore, it can be assumed that during the braking process, it is precisely in the near-surface layer of the friction elements that, under the action of an electric discharge and a thermal flash, cracks appear due to thermal fatigue of the material. These cracks develop as a result of the cooling of the surface layer and the emergence of a temperature gradient υ, thermal stresses in the near-surface layer reach the highest values. When the temperature rises, the nature of movement of the structural component materials that rub changes, the strength of the grain boundaries decreases and the rate of oxidation increases.

The analysis of the mechanism of wear of contacting pairs showed that in the conditions of aperiodic cyclic heating and forced cooling, the multiphase structure and thermal properties of individual phases have a great influence on the nucleation and development of microcracks. A certain role in the destruction of the material is played by the nature of the distribution of the network of microcracks on the surface.

Since flash temperatures can quickly reach several hundreds of degrees, such a jump in them contributes to the transition of the material to a state of plasticity, when frictional resistance is sharply reduced. Due to the fact that the duration of the interaction on the spots of actual contact of the microprotrusions is 10-3...10-6 s, it is not the property of the static strength of the surface layer of the materials of the friction pair that becomes important, but the occurrence of fatigue strength, since the crystal lattice of a solid reacts to actions after 10-5...10-8 s. Therefore, the restructuring of the structure of the surface layer under the action of external electric and thermal currents occurs precisely when the temperature field prevails, and by the time a constant temperature is reached, the surface layer of the periphery of the connection is already under the influence of certain residual thermal stresses.

The conducted studies showed that the speed of the thermal process has a significant influence on the main quality indicators of the surface layer of the connection periphery.

The high speed of electrothermomechanical processes causes significant structural transformations in the surface and near-surface layers, as well as a change in the physical and mechanical properties of the material at the periphery of the joint. In the process of friction, the zone of plastic deformation is not limited to the volume of micro-uniformities, but extends deep into the materials. At the same time, the materials of the surface and near-surface layers have a low density of dislocations. During sliding, dislocations accumulate at some distance from the surface, their density increases, which leads to the formation of microcavities in the near-surface layer of the periphery of the joint.

Analysis of the stress state of the surface periphery of the coupling during braking showed that the frictional forces contribute to its strengthening and the emergence of compressive residual stresses. Temperature deformations lead, as a rule, to the appearance of a strengthening effect in the surface layer, associated with the appearance of tensile residual stresses.

The intensity of forced cooling, which is determined taking into account the Bio criterion, has a significant impact on the depth of heating of the periphery of the connection. The intensity of electrothermomechanical friction affects the nature of the change in heating and cooling rates, as well as the distribution of temperatures along the thickness of the periphery of the joint. At the same time, it is advisable to investigate the influence of forced cooling conditions on the kinetics of the thermal process.

The proposed theoretical model of the mechanism of destruction as a result of electrothermomechanical load during friction confirms the assumption of the formation of a surface layer on the periphery of the joint with a low density of dislocations and intensive crack formation in the near-surface layers, which is in good agreement with the results of experimental research by Ts. Su.

Also worthy of attention are the works of L.M. Rybakova and L.I. Kukseneva, dedicated to the method of radiographic research of structural changes in the thin surface layer of metal during friction.

It is known that electrothermal and external loads applied to a solid cause strengthening of interatomic bonds, which, due to the heterogeneity of the structure of most solids, can have a local character. It is at the actual spots of contact of microprotrusions that local overvoltages occur, the most intense is the thermofluctuation process of breaking interatomic bonds, which leads to the destruction of the solid body. According to the kinetic concept of strength, the electrothermal movement of atoms, characterized by temperature, plays a significant role in the destruction of a solid body.

In fig. 3 the effect of temperature on the relative deformations σ/E of the periphery of the connection (where σп - strength limit; σs - stress caused by electrothermal impulses) is shown. This influence must be taken into account when creating various schemes for calculating residual microstresses, without knowing the values of which it is impossible to assess the physical condition of the surface layer of materials operating under repeated short-term load conditions.

The development of plastic deformations at the tip of a crack in a plate element of structures under the action of a local heat source is considered in [1]. A homogeneous isotropic plate with a crack of normal discontinuity was studied. The material of the plate was in an elastic-ideal plastic state and met the condition of plasticity of Saint-Venant. The end of the crack in the calculation scheme is represented in the form of a thin string with the distribution of deformations and stresses. It was assumed that the plastic deformations are concentrated along some slip lines emanating from the top of the crack. First, the problem of plane elasticity theory was solved, and then the boundary value problem of heat conduction theory was solved to estimate the temperature distribution on the surface of a solid plate. This made it possible to further determine its thermoelastic displacement potential. The local temperature change of the plate can be predicted by calculation. However, unfortunately, the proposed approach cannot be used in the study of electrothermomechanical friction of the considered combinations of nodes, since it is of a local nature.

The process of destruction during the interaction of microprotrusions of working friction pairs was studied in [1]. According to the thermomechanical theory of wear proposed by A. Kh. Dzhanakhmedov, the thermal stresses that exist in the surface and near-surface layers of contacting pairs are the result of a pulsed thermal impact on the friction surface [2]. The rapid increase in temperature at the contact spots of the microprotrusions of the contacting pairs is associated with thermal shock and is accompanied by the occurrence of significant thermal stresses σs and structural changes in the materials of the surface layers of the pair. The nature of the change in thermal stresses in the material of the periphery of the connection caused by surface flashes, which are pulses of heat flows [5], is illustrated by curves 1 and 2 in Fig. 4.

However, these studies did not establish the influence of design and operational parameters during the frictional interaction of contacting couples on the magnitude of thermal stresses occurring in the periphery of the connection.

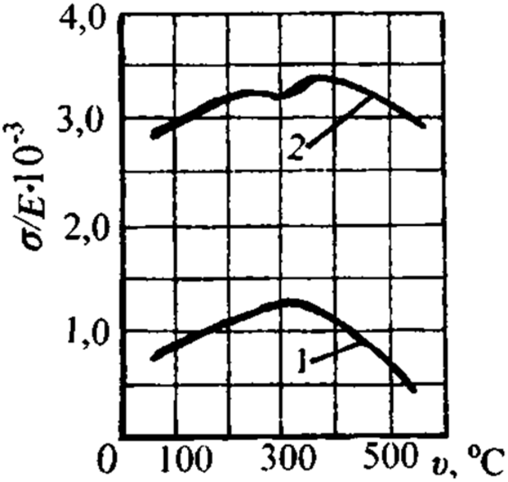

Figure 3 - The influence of surface temperature on the relative deformations of the material of the periphery of the connection: the curve 1 - σ_n/E; the curve 2 - σ_S/E

The process of merging microcracks is presented in the form of a hierarchical-subordinate system of ensembles of carriers of the destruction of the metal friction surface as a fractal set of points in the ultrametric space of states. The fractal dimension of the formed multifractal structure was determined using the procedure of the transition to chaos by sequentially dividing the set into fragments (a procedure inverse to Feigenbaum's scenario), which made it possible to assess the degree of destruction of the material. However, in the research, it was necessary to take into account the geometric interpretation of hierarchical trees, which are a network of microcracks limited by banks. By dividing them into triangles of different areas and configurations with three stress concentrators at their vertices, you can give a qualitative answer: "Will microcracks coalesce due to the action of hierarchical connection forces." The magnitudes of these forces in trees of different structures are determined by the number of triangles in them. The fewer triangles in the tree, the greater the strength of the hierarchical connection and the less likely the microcracks of the material will merge.

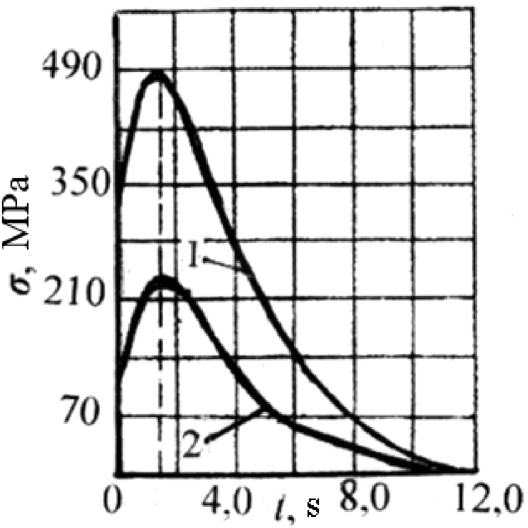

Figure 4 - Change of surface (curve 1) and radial (curve 2) thermal stresses in the material of the periphery of the connection depending on time.

The phenomenon of thermal destruction of materials during braking is a mechanism by influencing which the processes of friction and wear can be controlled. Knowing the main internal parameters of thermal destruction and the influence on them of the structure, materials, mode parameters, intensity of forced cooling, etc., it is possible to reasonably manage this phenomenon.

Thus, it can be noted that for a number of critical parts and structural elements (such as crankshafts) of marine vessels, the operation of which with the presence of cracks is prohibited according to the requirements of the maritime register of shipping, the most relevant issue is to determine the duration of the first and second stages, and not the question predicting the overall durability of the element. Therefore, for the issue of ensuring the safety of the operation of sea vessels, it is especially important to study the process of nucleation and growth of precisely small cracks [4]. The presence of a macrocrack in the crankshaft, the growth of which is described by linear fracture mechanics, allows us to conclude that such a shaft needs to be urgently replaced.

The relationship between the level of the maximum bending moment Mmaxi and the number of loading cycles Ni before failure, even with the strictest adherence to the identity of the tests of crankshafts for fatigue strength, due to the inhomogeneity of the material itself, has a pronounced random character. To take this circumstance into account, it must be assumed that the parameters of the fatigue curve are random variables subject to certain statistical distributions. In this regard, the durability of the crankshaft will be determined by the expression

$$T = \bar{T}\chi^{m} \qquad (1)$$

where $\bar{T}$ - average life of the crankshaft, calculated by the formula (1); χ - a random parameter whose distribution density has the form:

$$f(\chi) = \frac{1}{v(1-\varepsilon)}\left(\frac{\chi-\varepsilon}{1-\varepsilon}\right)^{\frac{1}{v}} \exp\left[-\left(\frac{\chi-\varepsilon}{1-\varepsilon}\right)^{\frac{1}{v}}\right] \qquad (2)$$

where v - the coefficient of variation; ε = 0,6 - fraction of mean fatigue limit Mmax0, below which fatigue damage does not accumulate.

Taking into account these factors, the probability of failure of the crankshaft due to fatigue failure during operation T is determined from the expression

$$F(T) = 1 - \exp\left\{-\left[\frac{\left(T/\bar{T}\right)-\varepsilon}{1-\varepsilon}\right]\right\} \qquad (3)$$

Directions for predicting the durability of the crankshaft involves the following stages of work: the endurance limit of the crankshaft is experimentally determined Mmax0, and according to the processing of the loading conditions of the crankshaft in operation - the values Mmaxi and number of loading blocks; formula (1) calculates the average durability $\bar{T}$; according to formula (2) for a given resource T, the probability of failure of the crankshaft due to fatigue failure is found (3).

Consideration of the theoretical model of the wear process (destruction) as a result of electrothermomechanical loading shows that the density of dislocations is low on the surface layers of the metal friction element, which leads to the appearance of cracks in its near-surface layers.

This model can serve as a basis for the constructive development of a metal friction element at the stage of its design, which was successfully implemented in [3].

From the above, it follows that during electrothermomechanical friction of microprotrusions of working pairs of part connections, the main factor contributing to the appearance and development of microcracks on the working surfaces of metal friction elements is the triboeffect, which under the influence of a mechanical field generates electric and thermal fields.

Conclusions and prospects for further researches.

1. A structural and parametric analysis of "shaft-sliding bearing" couplings was implemented to assess the energy levels of the surface and near-surface layers of their contacting pairs in order to rationally select coupling materials with high permissible levels of thermal and stress-strain states.
2. An attempt was also made to systematize the operational parameters and establish the regularities of their influence on the performance of combinations of parts of the STE with further generalization of the parameters on the basis of a stochastic approach to assess the regularities of the distribution of probabilities of the generalized parameters.
3. Taking into account the significant complexity of performing the specified calculations, it is suggested to use modern engineering tools when solving the problems of forecasting and reliability in the Mathcad environment.
4. Based on the analysis and classification of the main mated ship parts, characterize the main physical methods of mating parts "shaft-sliding bearing"

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