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ANALYSIS OF THE THERMOMECHANICAL CONDITION OF THE WORKING SURFACE OF "SHAFT-SLIDING BEARING" JOINTS’ PARTS IN SHIP REPAIR

Statement of the problem and its connection with important scientific or practical tasks.

Increasing the durability of ship technical equipment (STE) parts is directly related to the wear resistance of machine parts. That is, this is an actual direction of research. The durability of many machines is determined by the wear resistance of parts that have internal cylindrical surfaces that work in conditions of sliding friction.

The given analysis of literature data [1] about the quality of the surface layer of "shaft-sliding bearing" joints’ parts and its relationship with the operational properties of these products shows that the absence of defects such as burns and cracks significantly increases their performance and durability.

The properties of the composite material are considered in two directions. The first are those that depend exclusively on the geometric arrangement of the phases and their respective volume fractions, but do not depend on the sizes of the components at all. The second are those that depend on structural factors, such as the periodicity of the arrangement or particle sizes of two or more constituent phases.

It is indicated that frictional properties, such as wear resistance, can, for example, be significantly improved with the help of reinforcing inclusions: the tribological behavior is largely determined only by the surface material, it is less important if the reinforcing structure is fibrous or not.

Nanoparticles of SiC prevent the shift of grain boundaries and contribute to a significant improvement in creep resistance.

Improvements in creep resistance in other matrices for particle or tube composites are also observed, but generally low. However, increased creep resistance is obtained for mulito-zirconium composites and Si3N4 composites, to improved strength and viscosity relative to monolithic Al2O3, Al2O3-SiC nanocomposites also have increased wear resistance.

Grains in Al2O3—SiC nanocomposites wear out slowly, in contrast to monolithic Al2O3, where wear, as a rule, involves the removal of whole grains due to a relatively weak surface between the grains.

In addition, the absence of grain removal in the nanocomposite allows you to prepare a higher quality surface (and preserve it during wear) than is possible for monolithic Al2O3.

The excellent strength and viscosity of the nanocomposite is maintained at room temperature up to 1000°C. In addition, studies have shown that at higher temperatures, the creep resistance of Al2O3 is significantly increased due to the presence of SiC particles, which have higher strength and viscosity, increased wear resistance, a decrease in the creep rate at elevated temperatures, and excellent microstructural stability, which makes nanocomposites are an attractive alternative to monolithic ceramics for many structural applications.

According to this scheme, it is possible to calculate the heating and cooling rates both in the zone of contact of the circle with the part and outside it, it is possible to take into account the influence of heat exchange on the nature of the friction temperature distribution. In particular, it is possible to analytically study the non-stationary temperature field in the surface layer formed during intense friction [5].

The performed analysis of the physical and mechanical properties, as well as the coating thickness, made it possible to determine the stress state from the operating temperatures at the "coating-matrix" boundary and to develop the limit defect-free cycles of operational parts with a wear-resistant coating.

A large number of technological parameters are involved, which significantly affect the stress-strain state of coated parts. Obtained relations on the stress state of the "coating-matrix" system as a function of the physical and mechanical properties of the coating and matrix material, the main technological characteristics, especially prone to cracking of products with a wear-resistant coating.

The mechanical interpretation of crack formation does not take into account the influence of thermal processes, which are the dominant factor in the friction process.

Structural transformations cannot be the "independent" cause of the appearance of cracks. They can contribute to the growth of cracks that were formed under the action of thermal shock. Moreover, the process of transformation of temporary thermomechanical stresses takes place during a time sufficient for significant structural and phase changes in the surface layer, which in turn generates stresses that contribute to the further growth of cracks in contacting parts.

Analysis of recent research and publications.

Analysis of research on tribology showed that for the full life cycle of ship parts, operating costs are several times higher than the costs of manufacturing new equipment. Losses of funds from friction and wear in developed countries reach 4-5% of national income [2].

It is known that the task of increasing the wear resistance of a specific product often does not involve qualitative modification of the structural composition of the used material in its entire volume, but is transferred to the modification of the surface layer of the material, since the protection of parts from wear in some cases is solved by surface strengthening. In the general case, surface strengthening means increasing the hardness of the working surface of the part, which allows to increase the wear resistance [8].

A large number of works, in which various methods of strengthening are proposed, are devoted to increasing the mechanical characteristics that rub. Prospective directions for the development of surface-strengthening technologies involve the use of new methods of obtaining wear-resistant coatings, mainly using wear-resistant materials, that is, coatings based on compounds such as oxides, nitrides, and carbides. The use of reinforcing coatings made of heterogeneous materials leads not only to the modification of the surface layer, but also to the formation, in some cases, of a fundamentally new composite material of the surface layer, which has both high strength and sufficient plasticity, as well as increased wear resistance [1].

The study of the causes of the appearance of cracks is presented in works [7] from the standpoint of structural and phase transformations that generate the corresponding structural stresses and also have a private character and do not allow us to trace the true picture of the formation of defects such as cracks on the surface.

Setting the task.

The purpose of this study is to ensure the required quality of cylindrical surfaces of parts of STE with wear-resistant coatings, which are prone to crack formation by analyzing thermomechanical phenomena, which will allow to significantly reduce the formation of defects on their working surfaces.

Key words: ship technical equipment, defects of ship parts, "shaft-sliding bearing" connection, wear of surfaces.

The main research material

The conducted review of literature, domestic and foreign authors' inventions made it possible to systematize a number of works on increasing the level of reliability and features of the use of mating parts of the STE in combination with their maintenance bases.

The listed problems require a systemic solution based on resolving the contradictions between the aging of existing STE parts, for the renewal of which the state allocates insufficient funding, and maintenance bases that can potentially change their capabilities from degradation to a high level of development.

Here it can be emphasized that the current operating conditions of the aging STE fleet and the possible conditions for the development of maintenance and repair make it possible to structurally consider them as complex technical systems and propose new effective ways to increase the durability of existing STE. The latter circumstance opens up serious prospects for national manufacturers of STE parts.

Based on statistical patterns of loss of operability of the STE, analysis of the probabilities of the states of individual subsystems and elements, it becomes possible to build reliability models that adequately describe the behavior of systems with sufficient accuracy. Based on this, directions for increasing reliability are formed by increasing the probability of failure-free operation of individual elements, optimizing the structures of subsystems according to reliability criteria, as well as studying the probabilities of the state of subsystems in order to introduce elements of active and passive redundancy. The ultimate goal of such studies is the development of equipment with equal-resource subsystems that would reduce the costs of maintenance and repair to a minimum.

Using mathematical modeling [3], it is possible to assess the reliability of equipment at the stage of its creation when choosing options for structural construction and organizing future maintenance and repair operations.

A reliability model of such systems [4] is an analytical, statistical or physical way of displaying reality (machines, systems), which replaces them in the properties of formation and implementation of reliability, i.e. provides sufficient information about the reliability of the object being studied.

The more accurately the model describes the real object, the better it displays its reliability properties. However, increasing the accuracy of modeling is associated with the complication of the model itself. Therefore, it is rational to achieve a compromise between sufficient accuracy of modeling and the creation of models that are accessible for implementation.

Active factors supporting the required level of system reliability are operational and technical factors associated with the frequency of routine maintenance and repair of equipment if necessary.

Another group of operational factors is determined by the action of loads, the influence of the environment and operating conditions and is aimed at the formation of failures of elements and systems as a whole.

In general, a model that describes the reliability of systems can be presented implicitly as follows:

$$H = \Phi[F(r_i, \tau_i, N), U(r_i, \tau_i, \delta, T_c, T_n, N)],$$

where H is the reliability indicator of the system being studied;

F – (r1, r2, N)1 – is the functional representation of the structure of the system of interrelations of elements over a period of time r_i;

r_i is the reliability indicator of the i-th element;

N is the number of elements in the system;

U is the operator that takes into account the degree of influence of controlled operational factors on the reliability level of systems;

δ is the volume of work on technical maintenance of systems;

T_n is the period of technical maintenance of systems;

T_c is the time of decrease in system availability during maintenance.

Modern marine diesel engines require an increase in their fuel economy along with an increase in the efficiency of the turbocharging system and an optimization of the combustion chamber shape.

At the same time, cooling of diesel oil with water from the "hot" circuit of the diesel cooling system was introduced instead of air cooling in radiators, which led to an increase in the temperature of the diesel oil supplied to the crankshaft bearings. The conditions of their loading with the new dynamics of the combustion process and increased oil temperature were not studied by manufacturers with due completeness. Changes that increased the mechanical and thermal loading of the crankshaft bearings were not compensated for by measures that would increase the bearing capacity of the bearings.

Therefore, many marine diesel engines were found to have increased defects in the liners of the connecting rod and main bearings of the crankshafts. After several months of operation, the lead content in diesel oil was observed to increase above the limits established by current standards. Bearing clearances increased beyond the permissible values. It was necessary to unscheduledly replace the set of liners, causing significant economic damage. The defects of the working surface of the liners were in the form of squeezing out or wear of the babbitt layer with its frictional damage and were equally distributed to both main and connecting rod bearings. Then a one-time replacement of the complete set of main and connecting rod liners was required. This type of damage to the antifriction layer of the liners is typical for extreme pressures in bearings under conditions of oil starvation or low oil viscosity, when the thickness of the supporting oil layer decreases, boundary friction, progressive overheating, wear or squeezing out of the babbitt occur.

As a result, a connection was found between bearing defects and the parameters of the diesel engine and cooling system, as well as with the surface engineering indicators.

An increase in the fuel injection intensity by using high-pressure fuel pump (HPFP) washers caused an increase in the specific pressures in the connecting rod and main bearings. The criterion for the mechanical loading of the crankshaft connecting rod bearings is the value of the maximum load on the bearing, related to the area of the bearing projection on the plane normal to the direction of force [6]:

$$P = p_z{*} \text{ x } F_п / D \text{ x } L,$$

where: p_z is the maximum combustion pressure in the diesel cylinder; F is the piston area;

D, L are the diameter and width of the working surface of the bearing shell, respectively.

At the maximum combustion pressure pz equal to 8.2 MPa, the value of the average specific pressure P in the connecting rod bearings reached 19.4 MPa instead of 15.6 MPa at pz = 7.0 MPa. An increase in the bearing load by 18% could not but affect their performance, since the recommended values of the average specific pressure for liners filled with BK2 babbitt do not exceed 14.0 - 15.0 MPa [1].

One of the criteria for the need to repair mating parts is their ultimate wear, at which further normal operation of these mating parts is impossible.

A large number of damage sites are possible in the STE. The probability of their failure-free operation can be estimated statistically as a result of a series of experiments (Fig. 1) linking fault tolerance with the number of damages that have occurred [2], where p is a statistical estimate of the probability of system failure; n is the number of failed elements and/or connections between them; n1 is the maximum number of failed elements and/or connections at which the probability of failure is zero; n2 is the minimum number of failed elements and/or connections at which the probability of failure is one.

The resulting family of experimental points is conditionally divided into three zones:

zone I: 0 < n < n1, p = 0 — no more damage than n1; the system is absolutely operational;

zone II: n1 < n < n2, 0 <p < 1 — more damage than n1, but less than n2; the system remains operational only with a certain set of these damages;

zone III: n2≤ n; p = 1 — more damage than n2 - 1; the system is inoperable with any set of them.

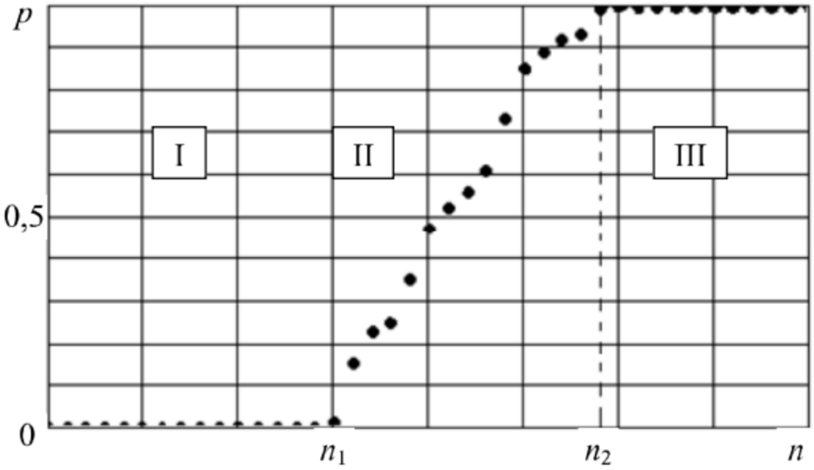

Fig. 1. Results of experimental statistical assessment of the probability of failure of the shaft-plain bearing coupling

It is obvious that the fault tolerance of the system depends on the values of n1 and n2 and is higher the longer the zero probability of failure is maintained (i.e., the greater n1, and the more the straight line approximating the experimental points in zone II is inclined to the abscissa axis (i.e., the greater the ratio n2 - n1).

One of the criteria for the need to repair mating parts is their ultimate wear, at which further normal operation of these matings is impossible.

The most important role is played by the conditions of contact of the surfaces. Friction is affected by the time of stationary contact, specific pressure on the contact, deformations, and the dimensions of the contact areas. As a result of the interaction of friction surfaces and the presence of surface energy, mechanical frictional bonds (elastic deformations and the introduction of microroughnesses) arise and stable atomic-molecular bonds (adhesion) are formed. In this case, a volumetric complex stress state arises in the contacting bodies and the formation of added masses of the boundary layer occurs [5].

External secondary conditions that have a significant effect on friction are characterized by a combination of factors. Firstly, these are the kinematics of motion (types of friction according to the kinematics of motion), the actual kinematic parameters of motion. These include the law (equations) of motion of a body (mechanism), the presence (absence) of reversibility of body motion; it is also necessary to take into account the trajectory of motion, the friction path, the speed and acceleration of the body. Secondly, these are the characteristics, conditions and parameters of dynamic effects. The mechanical behaviour of the system is influenced by dynamic factors: the laws of change of driving forces as a function of time, the presence and nature of oscillations, vibrations, impact, the number of loading cycles, the kinetic energy of a body or system of bodies, the work (power) of friction, the resistance to motion (friction force). The time factor of the process (the time of continuous operation, the duration of the process in the running-in mode of the friction unit and in the operating mode) is also taken into account.

The internal primary conditions of friction include those new phenomena and factors that arise on the friction contact and in the bodies themselves under the influence of the process of vision itself and the impact of the environment. The main thing here is the heating of the bodies, the growth of the friction temperature and the occurrence of a temperature gradient both in the bodies themselves and in the thin surface layer, leading to a change in the physical and mechanical properties of the materials.

Other scientific approaches are also used to assess the wear intensity of the friction pair "shaft journal - bearing shell". A joint solution of the basic equations of the energy theory of friction and wear of G. Fleischer and the molecular-mechanical theory of wear of I. V. Kragelsky can be used. According to [8], the best deterministic basis for wear intensity is a multiplicative dependence on dimensionless generalized criteria of the system. As applied to plain bearings, the lubricating fluids of which may also contain a certain amount of mechanical impurities, such a dependence has the form

$$l = a_0 \left(\frac{p}{HB_{1,2}} \right)^{a_1} \left(\frac{\lambda}{h} \right)^{a_2} \left(\frac{E_{1,2}}{\sigma_0} \right)^{a_3} (1+\alpha K)^{b_1} \left(1+\frac{HB_a}{HB_{1,2}} \right)^{b_2} \left(1+\gamma \frac{Sd_0}{V} \right)^{b_3}$$

where p/HB1,2 is a dimensionless complex characterizing the stress state in contact (p is the specific load, MPa; HB1,2 is the hardness of the working surfaces of the shaft and bearing, MPa); λ/h is a complex determining the contact mechanism (in the absence of mechanical impurities in the lubricating fluid)

$$\lambda = \sqrt{R_{a_1}^2 + R_{a_2}^2}$$

Here Ra1,2 is the standard deviation of surface roughness, μm; d0 is the reduced particle diameter; h is the thickness of the lubricating film; E1,2 /σ0 is a complex that takes into account the plasticity and fatigue strength of materials (E1,2 is the modulus of elasticity of the first kind, σ0 is the fatigue limit of materials, MPa); 1+αK is the concentration criterion of mechanical impurities (α is the coefficient taking into account the degree of influence of particle concentration on wear; K is the concentration, kg of abrasive/kg of liquid); HBa is the hardness of mechanical impurities, MPa; $1+\gamma \frac{Sd_0}{V}$ - particle shape criterion (γ is a coefficient that takes into account the degree of influence of particle geometry on mating wear; S, d0, V are, respectively, the surface, reduced diameter and volume of particles); a1, a2, a3, b1, b2, b3 - exponents determined on the basis of available information on the wear of materials or when testing similar samples.

Analysis of the deposits shows that due to the increased shortness of the working zone of the cylinder, the area of the spherical coating of the fiber increases due to the friction at this stage on the surface.

And this means that the destruction of the coating will occur even in the case when the technological stresses do not exceed the bond strength τ_{adh}.

With the existing operating stresses in the "cylinder-coating" system, the initial delamination in the area (-α, α) will remain.

From the above, it can be determined that in order to ensure the necessary reliability and durability of the cylindrical group with a coating, it is necessary to ensure a roughness of 0.8 ≤ Ra ≤ 1.2 when applying coatings on their working surfaces (Fig. 2). Such roughness can be achieved as a result of finishing grinding operations and subsequent finishing polishing. At the same time, the mathematical expectation of the delamination area M(α) will be within the capabilities of the technological process of applying the coating, in which the equilibrium state of the delamination area will be preserved under the action of technological stresses. In the case when, due to the roughness of the working surface of the cylinder, there is a system of delamination areas of the coating from the cylinder matrix (Fig. 2), a change in the stress intensity factor (SIF): SIF is possible due to their mutual influence. The dependence of the SIF on the relative distance between the areas of exfoliation is shown in Fig. 1.

As the distance d increases, the 2α/d coefficient decreases and the stress intensity can reach large values without disturbing the equilibrium state of the delamination areas.

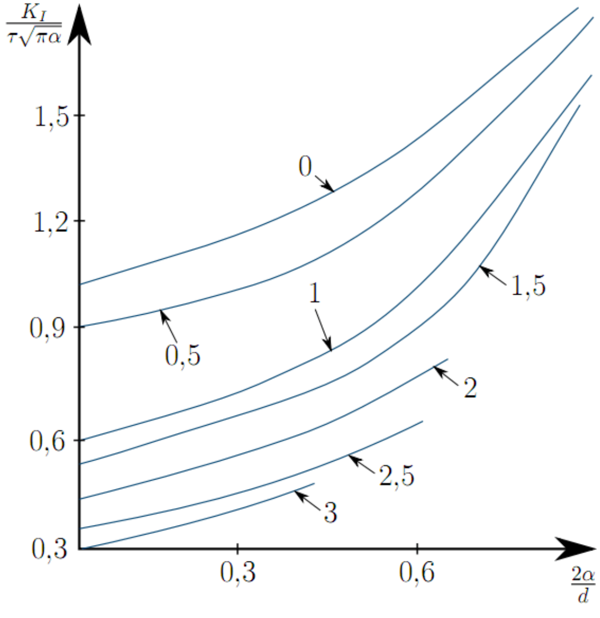

Fig. 2. Dependence of SIF Ki/tl/zha during longitudinal shear

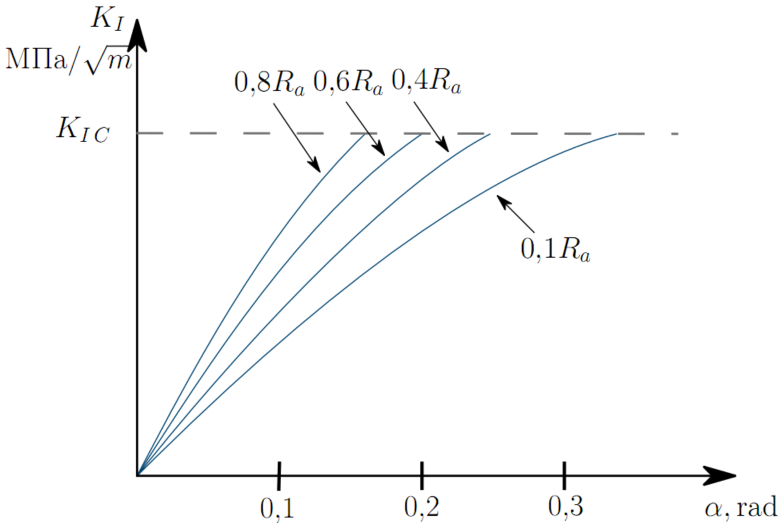

Fig. 3. Dependence of SIF on the peeling angle α and the roughness of the working zone of the cylindrical surface Ra.

In the case when, due to the roughness of the working surface of the cylinder, there is a system of delamination areas of the coating from the cylinder matrix, it is possible to change the SIF KI due to their mutual influence and operating conditions [1].

Conclusions and prospects for further research.

1. The mechanism of the formation of defects in the surface layer of ship parts of "shaft-sliding bearing" connections with wear-resistant coatings prone to the formation of cracks is determined.
2. The criteria for the formation of cracks were determined and their relationship with the investigated technological factors of the process of friction of the working surfaces of cylinders with wear-resistant coatings was established.
3. A mathematical model was developed that describes thermomechanical processes in the surface layer during friction of cylindrical surfaces with wear-resistant coatings, taking into account their partial delamination with the base material.

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