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RESEARCH

Energy Criterion of Oil Film Failure during Friction

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A B S T R A C T

The concepts developed by the thermodynamic theory of solid body strength and fracture are used to examine the conditions of lubricant film failure. We obtain a quantitative criterion that defines the lubricant film "defectness" - the critical value (constant for a given mineral oil) of the internal (thermal) energy density in the volume of the lubricant film. We propose analytic relations for evaluating scuffing in friction with lubrication and verify them experimentally on a full-scale stand for testing actual sliding bearings. We show the constancy of the critical value of the internal (thermal) energy density in the volume of the oil film at the moment of scuffing for an inactive mineral oil.

1. INTRODUCTION

We all know the friction is a global nature phenomenon of the energy transformation. Friction is subjected to energy balance equation and with thermodynamic point of view [1] is the process of two interrelated, oppositely directed and concurrent trends operating in a strained contact. According to the energy balance scheme (Fig. 1) for plastic deformation and fracture [2,3] presented below, equations for friction work W_{f}, frictional force F and friction coefficient μ (without lubrication) has view:

$$W_{\mathrm{f}} = \Delta U_{\mathrm{e}} + Q = \Delta U_{\mathrm{e}1} + \Delta U_{\mathrm{e}2} + \Delta U_{\mathrm{T}1} + \Delta U_{\mathrm{T}2} + \vec{Q}_1 + \vec{Q}_2, \quad (1)$$

$$\dot{W}_{\mathrm{f}} = \dot{U}_{\mathrm{e}} + \dot{Q} = \dot{U}_{\mathrm{e}1} + \dot{U}_{\mathrm{e}2} + \dot{U}_{\mathrm{T}1} + \dot{U}_{\mathrm{T}2} + \dot{\vec{Q}}_1 + \dot{\vec{Q}}_2, \quad (2)$$

$$F_l = \frac{\Delta U_{\mathrm{e}}}{l} + \frac{Q}{l} = \frac{\Delta U_{\mathrm{e}1} + \Delta U_{\mathrm{e}2}}{l} + \frac{Q_1 + Q_2}{l}, \quad (3)$$

$$F_{\mathrm{v}} = \frac{\dot{U}_{\mathrm{e}1} + \dot{U}_{\mathrm{e}2}}{v} + \frac{\dot{Q}_1 + \dot{Q}_2}{v} = F_{\mathrm{mechanical}} + F_{\mathrm{molecular}}, \quad (4)$$

$$\mu_l = \frac{\Delta U_{\mathrm{e}1} + \Delta U_{\mathrm{e}2}}{Nl} + \frac{Q_1 + Q_2}{Nl} = \mu_{\mathrm{adapt}} + \mu_{\mathrm{dis}} = \mu_{\mathrm{adapt}} + \mu_{\mathrm{T(dis)}} + \mu_{\vec{\mathrm{Q}}(\mathrm{dis})}, \quad (5)$$

$$\mu_{\mathrm{v}} = \frac{\dot{U}_{\mathrm{e}1} + \dot{U}_{\mathrm{e}2}}{Nv} + \frac{\dot{Q}_1 + \dot{Q}_2}{Nv} = \mu_{\mathrm{deformation}} + \mu_{\mathrm{adhesion}}, \quad (6)$$

where $\Delta U_e = V_f \Delta u_e$; $Q = V_f q$; $\vec{Q} = V_f \vec{q}$; $\dot{U}_e = V_f \dot{u}_e$; $\dot{u}_e = du_e/dt$ - is the rate of latent energy density change in the contact volumes; V_f - is the deformable (friction) volume; μ - friction coefficient; μ_{adapt} - adaptive friction coefficient; $\mu_{T(dis)}$ and $\mu_{\vec{Q}(dis)}$ - static and dynamical components of dissipative friction coefficient; ΔU_T - thermal component of internal energy; N - normal load; l - distance of friction; v -sliding velosity. The latent energy density Δu_e is an integral parameter of tribostate and damageability (failure (Δu_e^*)).

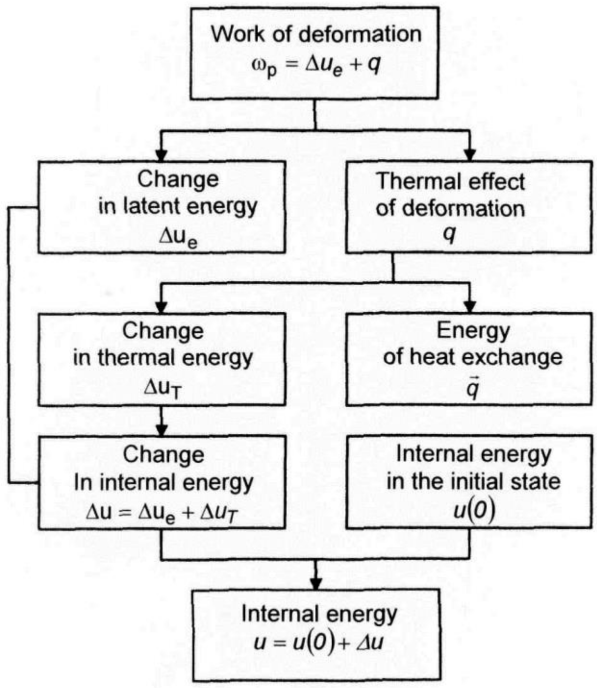

Fig. 1. Scheme of the energy balance for the plastic deformation of a solid body [1-3].

Thus, viewed thermodynamically, the work done by friction forces W_f (the friction power $\dot{W}_f$), the friction force F and the friction coefficient μ may be classified conventionally into two specific components with different kinetic behavior [3].

The first component is associated with microscopic mechanisms of adaptive type and relates to the change of latent (potential) energy ($\Delta u_{e_1}, \Delta u_{e_2}$) of various elementary defects and damages that are generated and accumulate in the deformable volumes of materials friction pair (Fig. 2).

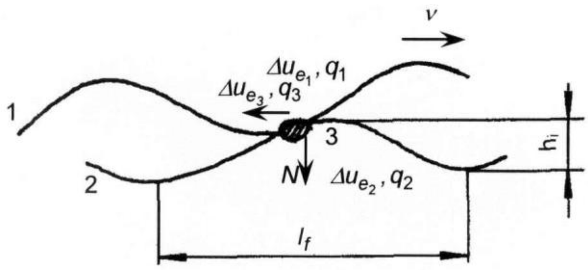

Fig. 2. Schematic view of elementary friction's contact [1,2].

This energy is a unique and integral characteristic of the submicro–and microstructural transformations that occur in plastically strained materials [1-3]. This energy is a measure of strain hardening and damageability of materials.

The second component is associated with microscopic mechanisms of dissipative type and relates to dynamic recovery processes in which latent energy and frictional heat are released (q_1, q_2). This energy originates in the motion and destruction of various elementary defects of opposite signs, the egress of these defects to the surface, the healing of reversible submicroscopic discontinuities, etc.

The ratios of the components Δu_{e_1} and Δu_{e_2} as well as q_1, q_2 of the balance vary over a wide range, depending on the physical, chemical, and structural properties of the materials that comprise the friction couple and the friction conditions.

During this transformation the friction surfaces are heated and the heat of friction transfer to oil film. Of course, in time an oil film may fail.

2. ABOUT SCUFFING UNDER DRY FRICTION

The thermodynamic concepts relating to the process of metal scuffing in friction without lubrication are examined in [1].

The basis of these concepts is the ergodynamic method [2,3] of description of the relationships of the process of plastic deformation, damage, and failure of solid bodies, based on the fundamental (most general) laws of thermodynamics, molecular kinetics, and dislocation theory in their dialectic unity.

Hypothesis has been proposed, in accordance with which the thin surface layer of the bearing material in the contact zone is in the superplastic state at the moment of scuffing.

The condition of scuffing in friction is equality of the velocity of viscoplastic flow of the thin surface layer of the bearing material, determining the growth of the real contact area and the shaft (counterbody) sliding velocity.

3. GENERALIZED QUANTITATIVE SCUFFING CRITERION

On the basis of use of the analytic apparatus (thermoactivation analysis) of the ergodynamic theory of strength and failure of solid bodies [2,3], reference [4] proposed and physically substantiated a generalized quantitative scuffing criterion - the critical (constant for a given friction pair) value of the specific friction power, determined by the intensity of mobility of the atoms in the thin surface layer of the friction pair materials under scuffing conditions.
The scuffing criterion has the form:

$$\omega_* = Ch_* D_{\mathrm{f}}^* = \omega_0^* \, exp\left(-\frac{U_{\mathrm{df}}}{kT}\right). \tag{7}$$

Here:

$$C = \frac{U_{\mathrm{v}}}{ga^2 V_0}; \tag{8}$$

$$\omega_0^* = \frac{U_{\mathrm{v}} h_* kT_*}{\hbar V_0}. \tag{9}$$

$$U_{\mathrm{df}} = U_{\mathrm{d}} + \beta_{\mathrm{f}} p_*^{2/3} - \frac{\alpha_f}{2}\tau_*^2 =$$
$$= U_{\mathrm{d}} + \beta b^2 p_*^{2/3} - \frac{\alpha}{2} c^2 \mu_*^2 \rho_*^2; \tag{10}$$

$$\alpha_{\mathrm{f}} = \frac{k_\sigma^2 V_0}{6G} c^2; \; \beta_{\mathrm{f}} = \frac{k_\sigma^2 V_0}{2K}.$$

Here ω - specific friction powers in dry friction ; h - thickness of plastically deformed layer of material in scuffing; D_{f} - coefficient of diffusional mobility of atoms in friction; U_{v}, U_{d} - free energies of vacancy formation and diffusion activation; U_{df} - free energy of vacancy diffusion activation in friction; k - Boltzmann's constant; T - absolute temperature; g - geometric factor, depending on crystal lattice type; a - atomic diameter; V_0 - atomic volume; $\hbar$ - Planck's constant; α_{f}, β_{f} - parameters characterizing "localness," macrononuniformity, and micrononuniformity of distribution of stresses acting on interatomic bonds; p - pressure; τ - specific friction force; μ - friction coefficient; b, c - parameters characterizing elastic properties of material and geometric parameters of asperities; k_σ - coefficient accounting for overstress on atomic bonds; V_0 - atomic volume; G - shear modulus; K - bulk compression modulus; * - critical values of parameters, corresponding to moment of scuffing.

The physical meaning of the criterion ω^* is connected with achievement by the friction surface of a definite deformation energy release flux density. The intensity of the elementary microscopic acts of formation of a junction of two metals (new surface), associated with emergence of the crystal structure defects to the surface (active center formation) and transition of the unstable atoms on the surface to a new equilibrium position (bond formation), reaches a magnitude such that the plastic deformation process will have a macroscopic avalanche-like nature - viscoplastic metal flow in the contact zone. The result of this is the formation of a common junction of the friction pair metals - a new (zero) surface.

Table 1. Value of Specific Friction Power at Moment of Scuffing for Various Metals and Alloys [5].

Material	$\overline{\omega}_*$, MW/m²
Pb	0,34
Al	0,51
AlSn9-1	0,401
Al+(0-50%)Sn	0,54
Al+(0-4,7%)Cu	0,56
Al+(0-19,6%)Mg	0,436
Al+(0-19,8%)Si	0,714
AMKO-1	0,56
AMKO-3	0,58
AMqK-1	0,364
AMqK-2	0,4
AMqK-3	0,413
Cu	0,99
Cu	0,95
LMts58-2	1,05
Ni	1,07
Ti	1,06
Fe	1,13
Steel 45	1,19

Table 1 shows the calculated (using the experimental data of [5]) values of the specific friction power ω^*, corresponding to the moment of scuffing, for various metals and their alloys. In all the experiments the counterbody material was steel. Analysis of the data of Table 1 shows that for the friction pair formed by two metals or their alloys the parameter ω^* is a constant quantity and is independent of the friction process conditions (p,v). This agrees well with the theoretical relations (7)-(10). Analysis of these relations shows that the various changes taking place in the surface layer of the friction pair materials influence the value of the complex parameter α_f, characterizing the localness and the macroscopic and microscopic nonuniformity of the distributions of the stresses acting on the interatomic bonds. This leads to change of the critical values μ_* and p_*, while the parameter ω^* remains constant (Table 2).

The parameter ω^* is the integral compatibility criterion and makes possible rational selection of the bearing material for a specific friction pair. For example, knowing the value of the specific friction power ω^* (Table 1), we can divide the materials and their alloys into like and unlike [6]. The combined operation of metals such as steel and copper (copper alloys) is unfavorable from the viewpoint of seizure resistance, since these metals and alloys form in essence like friction pairs.

The values of ω^* for these metals and alloys are approximately equal (respectively, 1.19 and 0.95 MW/m^2). At the moment of scuffing the processes of viscoplastic flow and damage of the friction pair materials will develop equally probably in the surface layer volumes of both the steel and the copper. For the friction pairs formed by metals such as steel and aluminum (aluminum alloys), or the still more favorable (from the viewpoint of seizure resistance) alloys based on tin and lead, the values of ω^* differ by 2 or 3 times from the values of ω^* for steel, i.e., these are unlike friction pairs, and in case of scuffing the processes of viscoplastic flow and damage of the surface layer will develop predominantly in the bearing material. In this case the shaft surface remains operable.

Table 2. Influence of Steel 45 Hardening Methods on Specific Friction Power Corresponding TO Scuffing. Friction Pair is Steel 45 Versus Steel 18KhGT, Lubricant is Vaseline Oil, v =4 m/sec [7].

Strengthening method	p, MPa	μ	ω^*_{lub}, $\frac{\text{MW}}{\text{m}^2}$	$\frac{\Delta\omega^*_{\text{lub}}}{\overline{\omega}^*_{\text{lub}}} \times 100$ %
Induction hardening, annealing at 400^{0}C	7,9	0,14	4,424	-0,9
Induction hardening, no annealing	8,3	0,13	4,42	-1,07
Nitrocementation, annealing at 300^{0}C	9,0	0,12	4,32	-3,2
Sillconizing	10,2	0,11	4,49	+0,49
Boronizing	13,0	0,09	4,68	+4,8

Note. $\overline{\omega}^*_{\text{lub}}$ =4,468 MW/m^2

The quantitative evaluation of friction pair compatibility based on the parameter ω^* is well confirmed by operation of the cited alloys. However the operation of friction assemblies with lubrication is of most interest in engineering practice. The experimental data on the critical values of the specific friction power at the moment of scuffing in friction with lubrication ω^*_{lub} differ significantly from the critical values ω^* in friction without lubrication and increase of the sliding velocity v (Tables 2 and 3).

Table 3. Influence of Sliding Speed of Steel Balls on Specific Friction Power Corresponding to Scuffing [5].

v, m/sec	ω^*_{lub}, MW/m^2
0,0237	6,9
0,56	83,6
4,0	734

It is well known that in the friction of lubricated surfaces the lubricant volume pumped through the contact zone of the rubbing bodies largely determines their effectiveness. The traditional lubricants (oils), being fluid, reduce (passivate) the energetic (activated) state of the friction surfaces quite well as a result of intense interaction of the lubricant molecules with the atoms of the activated friction surfaces. The lubricant film failure temperature T_{cr} determines the moment of onset of direct contact of the friction pair materials and (as a rule) their scuffing [8,9].

4. ENERGY CRITERION OF OIL FILM FAILURE

4.1. Thermodynamic theory of strength

Thermodynamic condition [2] for local failure has view:

$$u(\bar{r}_*,t_*)=u(\bar{r}_*,0)+\int_0^{t_*}\dot{u}(\bar{r}_*,t)\,\mathrm{d}\,t=u_*=\mathrm{const}. \quad (11)$$

Here $u(\bar{r}_*,0)$ - represents the density of the internal energy within the local macrovolume of the material in the initial (prior to deformation, t =0) state; $\dot{u}(\bar{r}_*,t)$ - represents the specific power of the internal energy sources in the local volume responsible for the failure; $\bar{r}_*$ - is the parameter which characterizes the coordinates (x_*,y_*,z_*) of the local volume responsible for failure.

In accordance with the modern thermodynamic concepts relating to the strength and fracture of materials [2,3], having a fundamental nature, failure of a volume of a material (critical "defectness") occurs when the internal energy density u (potential u_e and thermal u_T components) in this volume reaches the critical value u_*, constant for a given material. The criterion u_* is a single-valued and integral characteristic of limiting damage ("defectness") of a material. Thermal failure of the material is the particular case of this theory when the change of the potential component of the internal energy is negligibly small and can be neglected.

The temperature, however, is a quantitative measure of macroscopic manifestation of change of the density of the thermal (kinetic) u_T component of the internal energy of the material. We shall use these concepts to describe the case of oil film failure during friction with account for the kinetic characteristics of internal energy accumulation by liquid materials (oils).

4.2. The thermodynamic failure condition for solids

This condition [2] has the form:

$$u=u_0+\Delta u=u_*. \quad (12)$$

Here:

$$u_0=u_{\mathrm{e}0}+u_{\mathrm{T}0}, \quad (13)$$

$$\Delta u=\Delta u_\mathrm{e}+\Delta u_\mathrm{T}. \quad (14)$$

u - density of internal latent energy in volume of material; $u_{(0)},\Delta u$ - internal energy of material in initial state and its change during friction; $u_{\mathrm{e}(0)},u_{\mathrm{T}(0)}$ - potential and thermal components of internal energy of material in the initial state ($t=0$); $\Delta u_\mathrm{e},\Delta u_\mathrm{T}$ - change of potential and thermal components of internal energy of material during friction.

4.3. The thermodynamic failure condition for liquid oil films

We can say the liquid materials can not accumulate the energy of elementary defects as solids. There fore, in the particular case for liquid oil films $u_{\mathrm{e}0}$ and Δu_e are equal to zero, then the failure condition (12) can be written in the form:

$$u_\mathrm{T}=u_{\mathrm{T}0}+\Delta u_\mathrm{T}=u_\mathrm{T}^*. \quad (15)$$

Thus, Eq. (15) is the energetic condition of oil film failure in the contact [5]. In accordance with this equation the oil film fails if the density of the thermal (kinetic) energy u_T in its volume reaches the critical value u_T^*. Upon reaching this value the oil loses its lubricating properties and friction transitions to the regime of friction without lubrication.

As the condition of the absence of scuffing as a consequence of lubricant film failure we take the relation:

$$u_\mathrm{T}=u_{\mathrm{T}0}+\Delta u_\mathrm{T}<u_\mathrm{T}^*. \quad (16)$$

Dividing both, sides of (16) by the oil density p and the average oil heat capacity $\bar{c}_\mathrm{p}$, we obtain:

$$T=T_0+\Delta T<T_\mathrm{cr}=T_*. \quad (17)$$

Here:

$$u_{\mathrm{T}0}=\rho\,\bar{c}_\mathrm{p}T_0=\int_0^{T_0}\rho\,c_\mathrm{p}dT; \quad (18)$$

$$\Delta u_\mathrm{T}=\rho\,\bar{c}_\mathrm{p}\Delta T=\int_{T_0}^{T_*}\rho\,c_\mathrm{p}dT; \quad (19)$$

$$u_\mathrm{T}^*=\rho\,\bar{c}_\mathrm{p}T_*=\int_0^{T_*}\rho\,c_\mathrm{p}dT. \quad (20)$$

T_* - temperature of oil film failure; $T_0, \Delta T$ - surface temperature and. temperature flash.

Equation (17) is the well-known H. Block relation [8] for seizure, where T_{cr} is the critical temperature, upon reaching which the oil loses its lubricating properties and seizure of the surfaces takes place.

Table 4. Energetic Characteristics of Mineral Oils [5].

Oil	ρ, kg/m³	T_{cr}, ⁰C [9]	u_T^*, MJ/m³
Instrument Vaseline, GOST*1805-51 (MVP)	878	100	617
Transporter, GOST 982-50	880	180	751,6
Spindle, GOST 1642-50 (AU)	891	165	756
Compressor, GOST 5546-54 (KhF-12)	-	160	727,4
Turbine, GOST 32-53 (ZOUT)	895	120	663,2
Medicinal Vaseline, GOST 3164-52	875	20	483,4
Turbine, GOST 32-53 (ZOUT)	-	140	693
Industrial, GOST 5289-51(50)	906	140	705,5
Diffusion, GOST 7904-56 (DI)	-	20	491,7
Autotractor, GOST 1862-42 (AK-10)	920	150	733,6
Autotractor, GOST 1862-42 (AK-15)	930	140	724,2
Naphthene-paraffin fraction of MS-20 oil (NPS MS-20)	-	155	718,2
Aviation, GOST 1013-49 (MZS)	890	140	693
Aviation from Groznenskll crude, GOST 1012-29	905	210	824,2
Cylinder, TUM NP 233-47 (bright stock)	-	140	693
Ethyiene glycol	1110	125	833

Table 4 presents the values of u_T^* for known values of T_{cr} for mineral oils [9].

5. THE CALCULATION CORRELATIONS WITH SCUFFING TERMS UNDER LUBRICATED FRICTION

To establish the connection between the energetic characteristics of oil film failure in the contact of rubbing bodies and the friction process parameters we can use the relations presented in [10] for calculating the average temperature rise in the sliding contact friction zone. Since in the case of friction with lubrication the temperature of the thin lubricant film reflects the thermal state of the friction surfaces, then with accuracy adequate for practical purposes the values calculated for the friction surface temperature can be referred to the thermal state (temperature) of the oil film as well.

Thus, to calculate the average temperature rise in the friction zone for sliding contact on an area in the form of a square with side $2l$ we take a relation, which under the condition $L = vl/2a_1 > 5$ has the form:

$$\Delta T = \frac{1{,}064\omega\sqrt{a_1}\cdot l}{1{,}25\lambda_2\sqrt{a_1} + \lambda_1\sqrt{lv}}. \quad (21)$$

Multiplying both sides of (21) by $\rho\bar{c}_p$, we obtain:

$$\Delta u_T = \frac{1{,}064\omega_{lub}^*\sqrt{a_1}\cdot l\cdot\rho\cdot\bar{c}_p}{1{,}25\lambda_2\sqrt{a_1} + \lambda_1\sqrt{lv}}. \quad (22)$$

With account for (22) we transform the oil film failure condition (8) to the form:

$$u_T^* = u_{T0} + \frac{1{,}064\omega_{lub}^*\sqrt{a_1}\cdot l\cdot\rho\cdot\bar{c}_p}{1{,}25\lambda_2\sqrt{a_1} + \lambda_1\sqrt{lv}}. \quad (23)$$

Solving Eq. (23) for the specific friction power ω_{lub}^*, we obtain:

$$\omega_{lub}^* = \frac{\left[u_T^* - u_{T0}\right]\left(1{,}25\lambda_2\sqrt{a_1} + \lambda_1\sqrt{l\cdot v}\right)}{1{,}064\sqrt{a_1}\cdot l\cdot\rho\cdot\bar{c}_p}. \quad (24)$$

Here ρ - density of oil; $\bar{c}_p$ - average heat capacity of oil; l - length of contact spot; a_1, λ_1 - thermal and heat conductivity of bearing material; λ_2 - heat conductivity of counter-body material;
According to the data of [10], at high sliding speeds Eq. (21) has the form:

$$\Delta T = \frac{1{,}064\omega}{\lambda_1}\left(\frac{2a_1 l}{v}\right)^{1/2}. \quad (25)$$

In this case the relations (22)-(24) transform to the form:

$$\Delta u_T = \frac{1.064\omega_{lub}^*\rho\,\bar{c}_p}{\lambda_1}\left(\frac{2a_1 l}{v}\right)^{1/2}; \quad (26)$$

$$u_{\mathrm{T}}^{*} = u_{\mathrm{T0}} + \frac{1.064\omega_{\mathrm{lub}}^{*}\rho\,\bar{c}_{\mathrm{p}}}{\lambda_1}\left(\frac{2a_1 l}{v}\right)^{1/2}; \quad (27)$$

$$\omega_{\mathrm{lub}}^{*} = \frac{\left(u_{\mathrm{T}}^{*} - u_{\mathrm{T0}}\right)\lambda_1}{1{,}064\rho\,\bar{c}_{\mathrm{p}}}\left(\frac{v}{2a_1 l}\right)^{1/2}. \quad (28)$$

Here ω_{lub} - specific friction power in friction with lubrication.

The conditions (24), (28) are the quantitative criteria characterizing the moment of transition from friction with lubrication to the friction regime without lubrication. Because of breakdown of the lubricant film, i.e., upon satisfaction of the condition $\omega_{\mathrm{lub}} = \omega_{\mathrm{lub}}^{*}$ the oil loses its lubricity - the ability to intensely reduce the surface energy (passivate the surface) - and the friction regime without lubrication takes place, characteristic for which are its particular relations (see (7)-(10)).

Analysis of Eqs. (24), (28) shows that the scuffing criterion $\omega_{\mathrm{lub}}^{*}$ depends significantly on the critical value of the oil internal (thermal) energy density u_{T}^{*} and on the sliding speed (other conditions being the same). The larger the value of u_{T}^{*}, the larger the specific friction power $\omega_{\mathrm{lub}}^{*}$ at which oil film failure occurs, which creates conditions for increase of the area of real contact of dry unlubricated surfaces. The influence of this factor for the example of T_{cr} was studied in detail in [9]. The Influence of increase of the sliding speed v on increase of ω_{lub}^{*} shows up as a consequence of increase of the volume (flowrate) of the lubricant pumped through the friction zone, which leads to improvement of heat transfer and as a result of this to reduction of the temperature in the friction zone and the parameter u_{T0}. Table 3 shows the variation of the parameter $\omega_{\mathrm{lub}}^{*}$ as a function of the sliding velocity v for steel specimens in experiments with point contact and lubrication by mineral oils. The thermo physical properties of the shaft and ring materials $a_1, \lambda_1, \lambda_2$ have an influence on the parameter $\omega_{\mathrm{lub}}^{*}$.

Using Eq. (24), we can explain the experimental studies devoted to lubricant film failure in friction. For example, in the Matveevskii experiments on a four-ball friction machine [9] forced bulk heating of the oil to the temperature T_{cr} was performed with minimal friction power (to ensure the absence of friction heat in the contact as a of plastic deformation). If in formula (24) we set u_{T0} equal to u_{T}^{*}, we obtain a value of the specific friction power $\omega_{\mathrm{lub}}^{*}$ equal to zero.

The specific friction power parameter has broad experimental justification as a scuffing parameter [9]. The physical meaning of the criterion $\omega_{\mathrm{lub}}^{*}$ is associated with a definite intensity of friction heat formation [9].

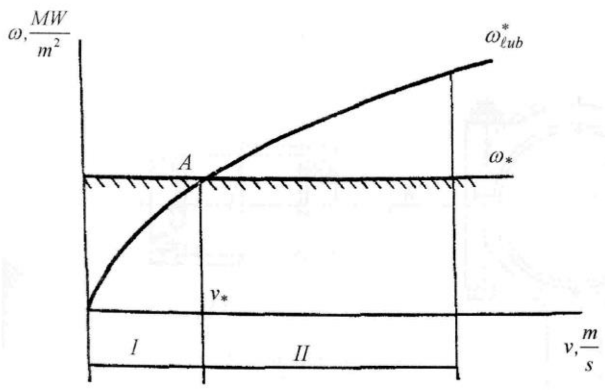

Fig. 3. Scuffing relationships in external friction.

The obtained theoretical relations (7), (15), describing the moment of scuffing onset, make it possible to identify the scuffing patterns in external friction. Joint examination of these two scuffing conditions (Fig. 3) shows that in the region bounded by segment I failure of the lubricant film and satisfaction of the scuffing condition $\omega_{\mathrm{lub}}^{*}$ do not lead to the formation of scuffing of the two surfaces over the entire nominal contact area, since the sufficient scuffing condition ω^{*} is not met, i.e., in this case we have not yet exceeded the energetic barrier [11], sufficient for formation of a junction of two metals over the entire nominal contact area. The microscuffing segments that form at individual points on the surface "heal themselves;" a form of friction interaction differing from scuffing dominates on the friction surface [12].

In the region bounded by segment II failure of the oil film automatically leads to scuffing formation over the entire surface bounded by the nominal contour, since in this case the sufficient scuffing (seizure) condition ω^{*} may be exceeded by several times. Thus, for example, segment II is characteristic for operation of the junctions of modern heavily loaded high-speed diesels. Achievement in the junction of the stable boundary friction regime and satisfaction of the condition $\omega_{\text{lub}} = \omega_{\text{lub}}^{*}$ led to scuffing and subsequently to seizure.

6. EXPERIMENT AND RESULTS

The experimental evaluation of the energetic condition of oil film failure during friction was performed on a full-scale stand with a pulsing load created by the hydraulic technique, which makes it possible to simulate the conditions of operation of the diesel engine connecting rod sliding bearings [5]. The tests were made with the actual bimetallic sliding bearings (bushings) with a layer of antifriction material of the alloys AlSn20-1 and CuPb30 (D=80 mm, H =34 mm, h_{B}=2,5 mm). Here H - bearing width; ε - diametral clearance; h_{B} - bearing thickness. The sliding bearings were tested in a pair with a steel 40KhNMA (induction hardened, HRC 50-55) shaft. Mark M14V diesel oil was used to lubricate the bearings. The experiments were made with shaft sliding velocity 4 m/sec.

The limiting load capacity of the friction pair was determined on the basis of marked increase of the friction power W_{f} and the temperature T_{oil} of the oil leaving the connecting rod bearing (Fig. 4) in the given loading stage p_{cr}, which was taken as the limiting (critical) value. The results of the experiments are shown in Table 5.

Table 5. Results of Experimental Studies of Load Capacity of AO20-1 and BrS30 Alloys on Full-Scale Test Stand [5].

Material	AlSn20-1	CuPb30
p_{cr}, MPa	48,0	35,0
W ,W	5157	9375
μ	0,011	0,027
T_{oil}, ^{0}C	120	115
$A^{\text{exp}} \cdot 10^{-4}$, m^2	14,4	12,5
$A^{\text{calc}} \cdot 10^{-4}$, m^2	13,3	11,9
ω_{lub}^{*}, MW/m^2	3,6	7,5

From the obtained experimental data ($\omega_{\text{lub}}^{*}, l, v$) we determined the oil film Internal energy density change Δu_{T} in the shaft-bushing contact at the moment of scuffing from formula (26); the friction surface flash temperature $\Delta T_{\text{f}} \cong \Delta T_{\text{oil}}$ –

$$\Delta T_{\text{oil}} = \frac{\Delta u_{\text{T}}}{\rho\, \bar{c}_{\text{p}}}; \tag{29}$$

the running value of the oil film internal (thermal) energy density:

$$u_{\text{Tf}} = T_{\text{oil}}\, \rho\, \bar{c}_{\text{p}}; \tag{30}$$

the critical value of the oil film internal (thermal) energy density and the friction surface temperature at the moment of scuffing:

$$u_{\text{T}}^{*} = u_{\text{T f}} + \Delta u_{\text{T}}. \tag{31}$$

$$T_{\text{cr}} = \frac{u_{\text{T}}^{*}}{\rho\, \bar{c}_{\text{p}}}. \tag{32}$$

Here $T_{\text{oil}}, \Delta T_{\text{oil}}$ - running value of oil temperature and critical value of oil temperature change in volume of oil film.

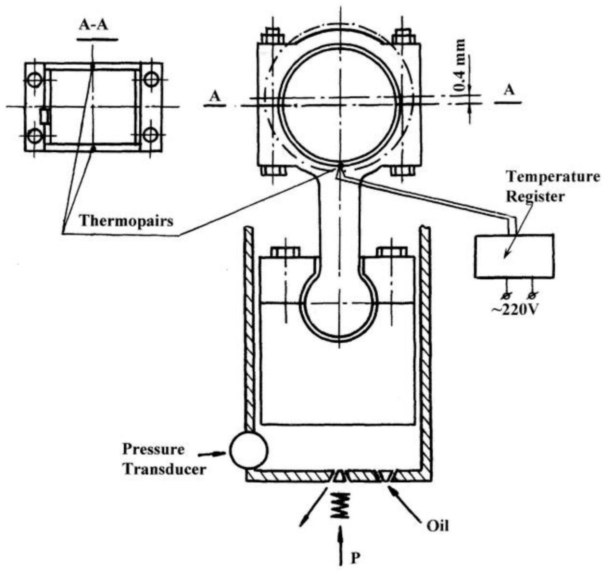

Fig. 4. The disposition of thermopairs for measuring of temperature T_{oil} of the oil leaving the connecting rod bearing.

In the calculations it was assumed that the temperature T_{oil} of the oil leaving the connecting rod bearing reflects the average bearing friction surface temperature.

The results of calculation of the oil film energetic characteristics and the friction surface temperature are shown in Table 6. For the given diesel oil grad (Table 6) the critical values u_{T}^{*} and T_{cr} are, respectively, 733 MJ/m³ and 150 °C.

Table 6. Results of Calculation of Oil Film Energetic Characteristics Corresponding to Moment of Scuffing [5].

Material	AlSn20-1	CuPb30
u_{T}	682	673
$\Delta u_{\mathrm{T}}^{*}$	43	54
u_{T}^{*}	725	727
T_{oil}	120	115
ΔT_{oil}	25,5	31
T_{cr}	145,5	146

Thus the experiment results confirm reliably the assumed energetic scuffing condition (15). The critical magnitude of the oil film internal (thermal) energy density for a given inactive mineral oil grade is independent of the bearing material grade and the friction process conditions and is a physical constant of the tribosystem scuffing process.

The obtained results agree well with the fundamental concepts of the ergodynamic theory of strength [2,3], in accordance with which the integral measure of material susceptible to damage is the critical (constant for a given material) value of the internal energy density, and also with the H.Block hypothesis [8] on constancy of the overall seizure temperature for a given mineral oil grade.

7. PRACTICAL RESULTS

These theoretical and experimental studies of the process of metal scuffing (seizure) in boundary friction make it possible to identify the relations establishing the connection between the critical characteristics tribosystem operation with the friction process parameters $(l = f(P)v)$, the properties of the bearing and lubricant materials (k), and the friction assembly constructive parameters $D; l = f(\varepsilon); H$. These relations have the form:

$$\omega_{\mathrm{lub}}^{*} = k \cdot v^{1/2} l^{-1/2}; \qquad (33)$$

$$W_{\mathrm{f}}^{*} = k \cdot (vl)^{1/2} H; \qquad (34)$$

$$\tau^{*} = k \cdot (vl)^{-1/2}; \qquad (35)$$

$$F^{*} = k \cdot v^{-1/2} l^{1/2} H; \qquad (36)$$

$$k = \frac{\Delta T_{\mathrm{oil}}^{*} \lambda_1}{1{,}064\sqrt{2a_1}} = const; \qquad (37)$$

$$\Delta T_{\mathrm{oil}}^{*} = T_{*} - T_{\mathrm{oil}}^{*} = const. \qquad (38)$$

Here F - friction force; W_{f} - friction power; v - counterbody sliding velocity.

The quantity $\Delta T_{\mathrm{oil}}^{*}$ in (37) is formed by the difference of two constant parameters - the critical value of the oil temperature $T_{*}(u_{\mathrm{T}}^{*})$ and the value of the limiting oil operating temperature $T_{\mathrm{oil}}(u_{\mathrm{T}})$, at which the stable boundary friction regime is reached. The physical meaning of the parameter T_{oil} is the value of the oil temperature on the Walter temperature-viscosity relation (Fig.5) at which the minimal viscosity of the oil is reached (with accuracy adequate for practical purposes). For example, for M14V diesel oil the value of T_{oil} is 115-120°C (Table 5). Reaching of the minimal oil viscosity in the junction means exhaustion of the hydrodynamic properties of the oil layer and transition to the stable boundary (direct) friction regime or, as follows from the Newton equation for the viscous friction force of liquids:

$$\tau_{\mathrm{oil}(\mu \cong 0)} = \frac{dv}{dh} \cong 0. \qquad (39)$$

Here μ - viscosity of oil.

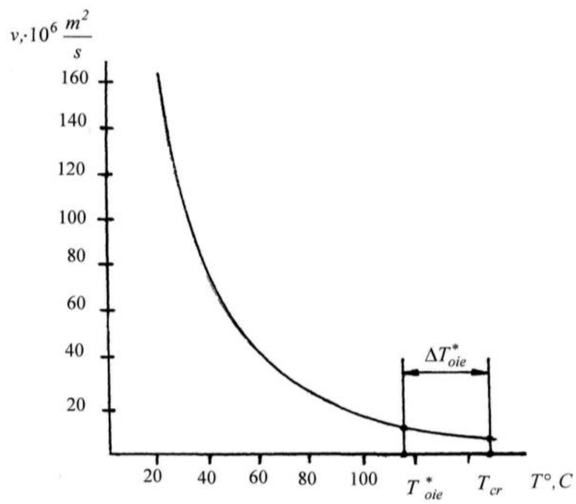

Fig. 5. The field of two critical temperatures of lubricating oils.

These studies of the metal scuffing (seizure) process made it possible to develop an analytic engineering technique for determining the seizure resistance characteristics of bearing materials in diesel engine sliding bearings [5].

8. CONCLUSION

- In general case the oil film failure under friction we may characterize with using the energy criterion.
- The energy theory of the oil film failure we may examine as a particular case of a general energy theory of failure.
- In accordance with the thermodynamic theory of failure the oil film fails if the density of the thermal (kinetic) energy in its volume reaches the critical value.
- The experiment results confirm reliably the assumed energetic criterion of the oil film failure. The critical magnitude of the oil film internal (thermal) energy density for a given inactive mineral oil grade is independent of the bearing material grade and the friction process conditions and it is a physical constant of the tribosystem scuffing process.
- The theoretical and experimental studies of the process of metal scuffing (seizure) under friction with lubrication make it possible to identify the relations establishing the connection between the critical characteristics tribosystem operation with the friction process parameters, the properties of the bearing and lubricant materials, and the friction assembly constructive parameters.
- The experimental analysis of the oil film failure for heavy loaded diesel engine sliding bearings has allowed display the existence of two critical temperatures for mineral lubricant. Correlation between these two critical temperatures determines the critical state (scuffing) for real heavy loaded engines.

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