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THERMAL MODELS OF HD AND EHD LUBRICANT FILM

Abstract

For the case of the failure of the lubricant film under hydrodynamic lubrication a common thermodynamic theory of strength is considered. According to this theory the failure occurs when the internal energy density (potential and thermal components) in the bulk of material reaches a constant value for a given material. A special case of this theory is when only the density of heat (kinetic) component of internal energy is taken into account. This is due to the kinetic peculiarities of accumulation of internal energy of liquid materials. This condition determines the limit state for liquid lubricants - mineral oils. In the case of hydrodynamic lubrication the practical solution of this power criterion is achieved by using a more convenient criterion - temperature flashes in the lubricant film.

When analyzing the regularities of friction under EHD lubrication two separate and possible effects are taken into account. The first one is regularity of plastic deformation (states and properties) at Hertzian contact of solids. The second one is the state and properties of the oil film under irregular and hydrostatic compression. The original structural model of oil film by EHD lubrication in the form of a rotary oscillating cells with elastic interactions is proposed. This is similar to the Rayleigh-Benard cells. It is possible that the size of the cells are an order about nano level (type fullerene's form or mechanical quantum). The oil film dissipates energy in the direction of relative motion of bodies. This oil film has the highest dissipative properties. Here, the work of the external forces is almost completely dissipated in these oil film structures. The concept of temperature for a such film has almost no meaning. The load of the EHD film is very high because it is elastic and energy dissipation is reversible.

Key words: *friction; energy balance; energy density; lubricant; temperature; nanostructure*

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 [1,2] is the process of two interrelated, oppositely directed and concurrent trends operating in a strained contact.

According to the energy balance scheme (Figure 1) for plastic deformation and fracture [3-5] presented below, equations for friction work W_f, frictional force F and friction coefficient μ (without lubrication) has view:

$$W_f = \Delta U_e + Q = \Delta U_{\mathrm{e}_1} + \Delta U_{\mathrm{e}_2} + \Delta U_{\mathrm{T}_1} + \Delta U_{\mathrm{T}_2} + \vec{Q}_1 + \vec{Q}_2, \tag{1}$$

$$\dot{W}_f = \dot{U}_e + \dot{Q} = \dot{U}_{\mathrm{e}_1} + \dot{U}_{\mathrm{e}_2} + \dot{U}_{\mathrm{T}_1} + \dot{U}_{\mathrm{T}_2} + \dot{\vec{Q}}_1 + \dot{\vec{Q}}_2, \tag{2}$$

$$F_l = \frac{\Delta U_{\mathrm{e}}}{l} + \frac{Q}{l} = \frac{\Delta U_{\mathrm{e}_1} + \Delta U_{\mathrm{e}_2}}{l} + \frac{Q_1 + Q_2}{l}, \tag{3}$$

$$F_{\mathrm{v}} = \frac{\dot{U}_{\mathrm{e}_1} + \dot{U}_{\mathrm{e}_2}}{v} + \frac{\dot{Q}_1 + \dot{Q}_2}{v} = F_{mechanical} + F_{molecular}, \tag{4}$$

$$\mu_l = \frac{\Delta U_{\mathrm{e}_1} + \Delta U_{\mathrm{e}_2}}{Nl} + \frac{Q_1 + Q_2}{Nl} = \mu_{adapt} + \mu_{dis} = \mu_{adapt} + \mu_{T(dis)} + \mu_{\vec{Q}(dis)}, \tag{5}$$

$$\mu_{\mathrm{v}} = \frac{\dot{U}_{\mathrm{e}_1} + \dot{U}_{\mathrm{e}_2}}{Nv} + \frac{\dot{Q}_1 + \dot{Q}_2}{Nv} = \mu_{deformation} + \mu_{adhesion}, \tag{6}$$

where $\Delta U_{\mathrm{e}} = V_{\mathrm{f}} \Delta u_{\mathrm{e}}$; $Q = V_{\mathrm{f}} q$; $\vec{Q} = V_{\mathrm{f}} \vec{q}$; $\dot{U}_{\mathrm{e}} = V_{\mathrm{f}} \dot{u}_{\mathrm{e}}$; $\dot{u}_{\mathrm{e}} = \mathrm{d}u_{\mathrm{e}}/\mathrm{d}t$ - 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; $\mu_{\mathrm{T(dis)}}$ and $\mu_{\vec{\mathrm{Q}}\mathrm{(dis)}}$ - static and dynamical components of dissipative friction coefficient; ΔU_{T} - thermal component of internal energy; N - normal load; l - distance of friction; v - sliding velocity. The latent energy density Δu_{e} is an integral parameter of tribostate and damageability (failure (Δu_{e}^*)).

Thus, viewed thermodynamically, the work done by friction forces W_{f} (the friction power $\dot{W}_{\mathrm{f}}$), the friction force F and the friction coefficient μ may be classified conventionally into two specific components with different kinetic behaviour [3-5]. The first component is associated with microscopic mechanisms of adaptive type and relates to the change of latent (potential) energy ($\Delta u_{\mathrm{e}_1}, \Delta u_{\mathrm{e}_2}$) of various elementary defects and damages that are generated and accumulate in the deformable volumes of materials friction pair (Figure 2).

This energy is a unique and integral characteristic of the submicro – and micro-structural transformations that occur in plastically strained materials [3-5]. This energy is a measure of strain hardening and damageability of materials.

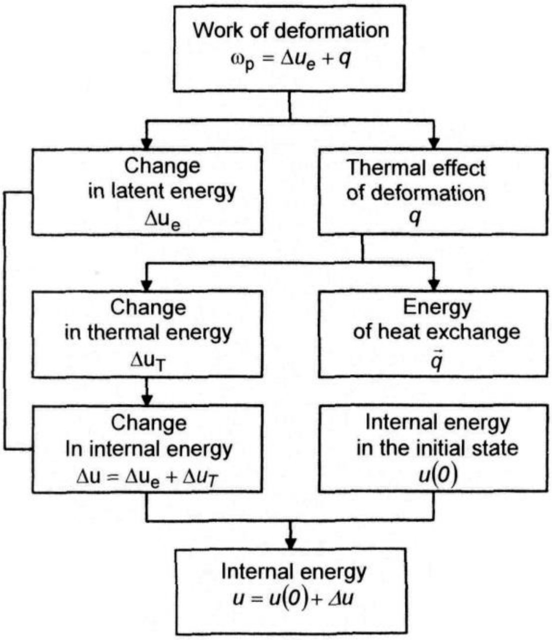

Figure 1: Scheme of the energy balance for the plastic deformation of a solid body [3-5]

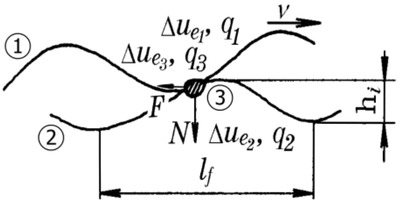

Figure 2: Schematic view of elementary friction’s contact [1,2]

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. Energy criterion of oil film failure

2.1. Thermodynamic theory of strength

Thermodynamic condition [3,4] for local failure has view

$$u(\bar{r}_*, t_*) = u(\bar{r}_*, 0) + \int_0^{t_*} \dot{u}(\bar{r}_*, t)\,\mathrm{d}\,t = u_* = \mathrm{const}. \qquad (7)$$

Here $u(\bar{r}_*, 0)$ - represents the density of the internal energy within the local macro-volume 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 [3,4], 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).

2.2. Thermodynamic failure condition for solids

This condition [3,4] has the form

$$u = u_0 + \Delta u = u_*. \qquad (8)$$

Here

$$u_0 = u_{\mathrm{e}0} + u_{\mathrm{T}0}, \qquad (9)$$

$$\Delta u = \Delta u_\mathrm{e} + \Delta u_\mathrm{T}. \qquad (10)$$

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.

2.3. Thermodynamic failure condition for liquid oil films

We can say the liquid materials can not accumulate the energy of elementary defects as solids. Therefore, in the particular case for liquid oil films $u_{\mathrm{e}0}$ and Δu_{e} are equal to zero, then the failure condition (8) can be written in the form

$$u_{\mathrm{T}} = u_{\mathrm{T}0} + \Delta u_{\mathrm{T}} = u_{\mathrm{T}}^{*}. \qquad (11)$$

Thus, Eq. (11) is the energetic condition of oil film failure in the contact [6]. 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

$$u_{\mathrm{T}} = u_{\mathrm{T}0} + \Delta u_{\mathrm{T}} < u_{\mathrm{T}}^{*}. \qquad (12)$$

Dividing both sides of Eq. (12) by the oil density ρ and the average oil heat capacity $\bar{c}_{\mathrm{p}}$, we obtain

$$T = T_0 + \Delta T < T_{\mathrm{cr}} = T_{*}. \qquad (13)$$

Here

$$u_{\mathrm{T}0} = \rho\,\bar{c}_{\mathrm{p}} T_0 = \int_0^{T_0} \rho\, c_{\mathrm{p}} dT\,;\ \ \Delta u_{\mathrm{T}} = \rho\,\bar{c}_{\mathrm{p}} \Delta T = \int_{T_0}^{T_*} \rho\, c_{\mathrm{p}} dT\,;\ \ u_{\mathrm{T}}^{*} = \rho\,\bar{c}_{\mathrm{p}} T_{*} = \int_0^{T_*} \rho\, c_{\mathrm{p}} dT\,, \qquad (14)$$

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

Equation (13) is the well-known H. Block relation [7] 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 1 presents the values of u_{T}^{*} for known values of T_{cr} for mineral oils [8].

3. 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 [9] 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 [9], which at high sliding speeds has the form

$$\Delta T = \frac{1{,}064\omega}{\lambda_1}\left(\frac{2a_1 l}{v}\right)^{1/2}. \qquad (15)$$

In this case the relations (15) transform to the form

$$\Delta u_{\text{T}} = \frac{1.064\omega^{*}_{\text{lub}}\rho\,\bar{c}_{\text{p}}}{\lambda_1}\left(\frac{2a_1 l}{v}\right)^{1/2}; \qquad (16)$$

$$u^{*}_{\text{T}} = u_{\text{T0}} + \frac{1.064\omega^{*}_{\text{lub}}\rho\,\bar{c}_{\text{p}}}{\lambda_1}\left(\frac{2a_1 l}{v}\right)^{1/2}; \qquad (17)$$

$$\omega^{*}_{\text{lub}} = \frac{\left(u^{*}_{\text{T}} - u_{\text{T0}}\right)\lambda_1}{1{,}064\rho\,\bar{c}_{\text{p}}}\left(\frac{v}{2a_1 l}\right)^{1/2}. \qquad (18)$$

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

Table 1: Energetic characteristics of mineral oils [6]

Oil	ρ, kg/m^3	T_{cr}, ^{0}C [9]	u^{*}_{T}, MJ/m^3
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 GroznenskII crude, GOST 1012-29	905	210	824.2
Cylinder, TUM NP 233-47 (bright stock)	-	140	693
Ethyiene glycol	1110	125	833

The condition (18) 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.

Analysis of Eq. (18) 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 increase of the sliding speed *v* on increase of $\omega_{\mathrm{lub}}^{*}$ 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}. The thermo-physical properties of the shaft and ring materials $a_1, \lambda_1, \lambda_2$ have an influence on the parameter $\omega_{\mathrm{lub}}^{*}$.

4. HD 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 [6,10].

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 is: H - bearing width; ε - diametral clearance; h_{B} - bearing thickness. The sliding bearings were tested in a pair with a steel 40NiCrMo6 (DIN) (induction hardened, HRC 50-55) shaft. Mark SAE40 diesel oil was used to lubricate the bearings. The experiments were made with shaft sliding velocity of 4 m/s. Special design of thermocouple has determined the real temperature into oil jet (stream) flowing out of connecting rod bearing (Fig. 3). 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. 3) in the given loading stage p_{cr}, which was taken as the limiting (critical) value. The results are given in Table 2.

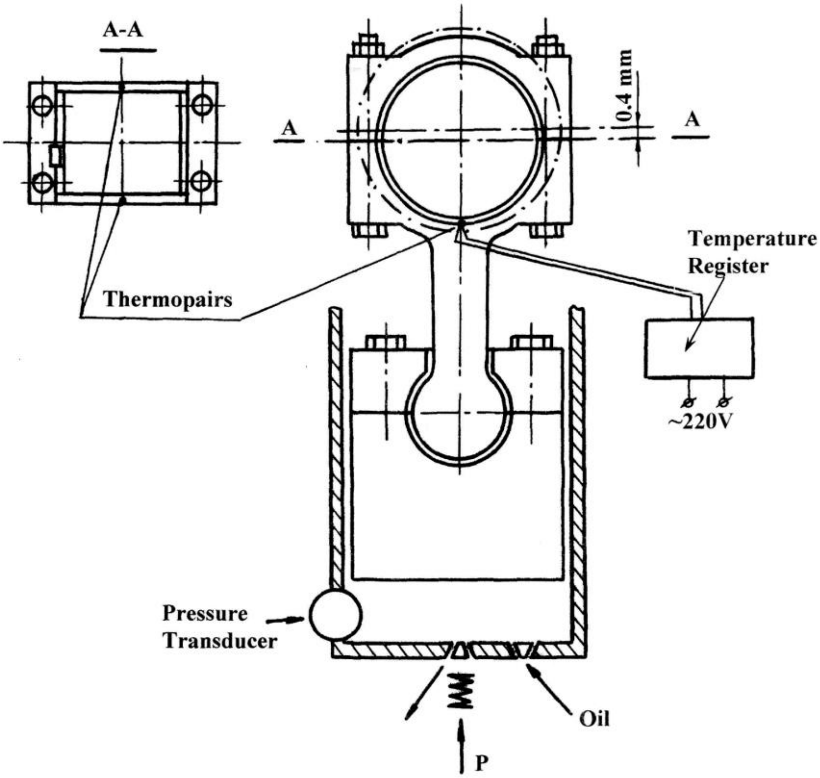

Figure 3: The disposition of thermopairs for measuring of temperature T_{oil} of the oil leaving the connecting rod bearing

Table 2: Results of experimental studies of load capacity of AlSn20-1and CuPb30 alloys on full-scale test stand [5,10]

Material	AlSn20-1	CuPb30
p_{cr}, MPa	48.0	35.0
W, W	5157	9375
μ	0.011	0.027
T_{oil}, °C	120	115
$A^{\mathrm{exp}} \cdot 10^{-4}$, m2	14.4	12.5
$A^{\mathrm{calc}} \cdot 10^{-4}$, m2	13.3	11.9
$\omega^{*}_{\mathrm{lub}}$, MW/m2	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 (16); the friction surface flash temperature $\Delta T_{\text{f}} \cong \Delta T_{\text{oil}}$:

$$\Delta T_{\text{oil}} = \frac{\Delta u_{\text{T}}}{\rho\,\bar{c}_{\text{p}}}; \qquad (19)$$

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

$$u_{\text{Tf}} = T_{\text{oil}}\rho\,\bar{c}_{\text{p}}; \qquad (20)$$

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

$$u^{*}_{\text{T}} = u_{\text{T f}} + \Delta u_{\text{T}}; \qquad (21)$$

$$T_{\text{cr}} = \frac{u^{*}_{\text{T}}}{\rho\,\bar{c}_{\text{p}}}. \qquad (22)$$

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. 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 given in Table 3. For the given diesel oil grad (Table 3) the critical values u^{*}_{T} and T_{cr} are, respectively, 733 MJ/m^3 and 150°C.

Table 3: Results of calculation of oil film energetic characteristics corresponding to moment of scuffing [6,10]

Material	AlSn20-1	CuPb30
u_{T}	682	673
Δu^{*}_{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 [11]. 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 [3-5], 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 [7] on constancy of the overall seizure temperature for a given mineral oil grade.

5. EHD lubrication hypothesis

It is known that the EHD lubricant type has significantly higher performance (capacity for work), than HD lubricant type. Modern tribology [11] high performances lubricant when EHD explains with the effect of increasing the viscosity of the lubricant when it is compacted. It is known that for most mineral oils use high pressures can lead to a huge increase in viscosity. Oil between the surfaces at high pressures in the contact area, behaves actually as hard separating layer. This process explains why many mechanisms in practice operate under much severer conditions than can allow the classical theory. Naturally the question arises about the healthy lubrication EHD in its temperature aspect. Is it possible to apply temperature fracture criterion of an oil film that successfully explains the loss of efficiency at HD lubricant?

We can examine the Hertzian scheme of contact under friction (Fig. 4).

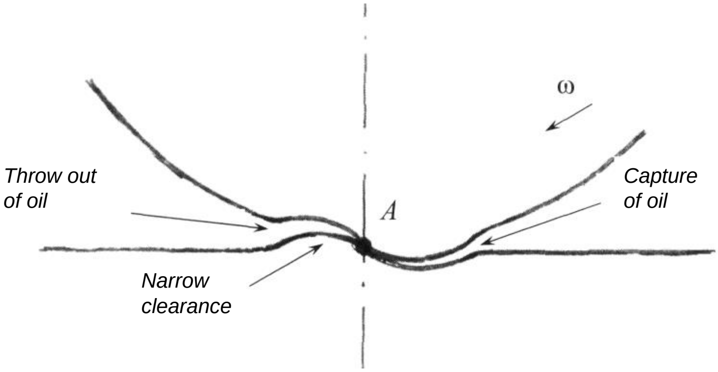

Figure 4: Model of elastic perfectly smooth roller on elastic and smooth surface

In proximity of Hertzian contact with size of a material point A due to elasticity (Poisson effect) two equilibrium (elastic) hemisphere (roughness)-on roller and on the surface are formed. If there is a thin film of lubricant between the surfaces this two roughnesses operate as elements of a gear pump. Roughness of roller captures lubricant, which is getting into the zone of Hertzian contact of material point A and is hydrostatically compressed and then pressed out into disclose contact on surface roughness. Here, we may consider these three stages of contact formation of equilibrium roughnesses when EHD lubrication on an example of mechanical model of EHD lubricant (Fig. 5).

In the first stage (a) an oil film is captured with elastic roughness in the cavity under the roughness. In the second stage (б) an oil film is hydrostatically compressed in this cavity. At the third stage (c) a narrow gap begins to form between these two roughnesses and compressed lubricant at high speed flow from the field of hydrostatic compression, creating a peak pressure.

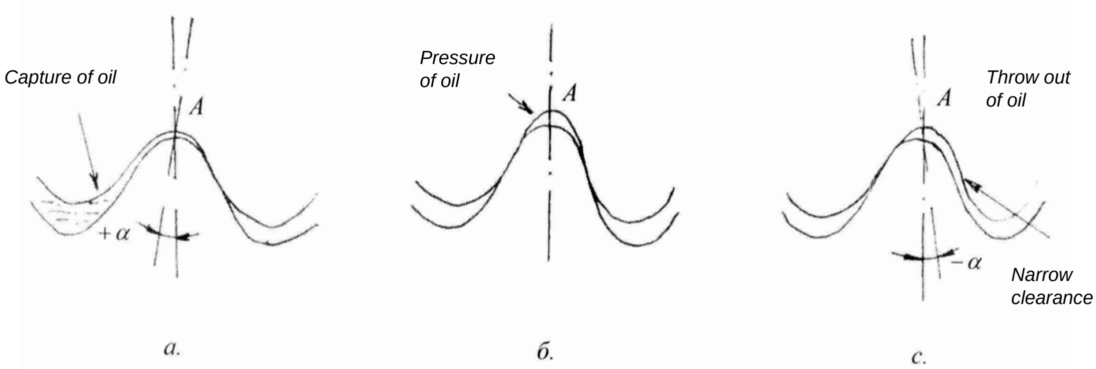

Figure 5: Three stages of forming contact with EHD lubrication

Proposed model for Hertzian lubricant contact is fully corresponds with the known curve of pressure distribution in contact EHD (Fig. 6).

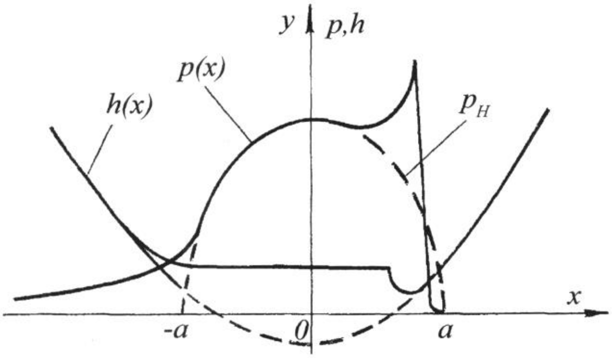

Figure 6: Model of Ertel-Grubin EHD film: p_H - Hertzian pressure; $p(x)$- current pressure layer; $h(x)$ - the current thickness of the lubricating layer; a - half width of contact area.

Left and central parts of pressure distribution in elasto-hydrodynamical film of lubricant corresponds to the areas of capture and compression. The right part (pressure peak) corresponds to condition of high-speed flow of compressed lubricant through a narrow gap on the third stage of forming contact EHD lubrication.

The question about the nature and state of the oil film in EHD lubrication is directly linked to the question of temperature fracture criteria for lubricant. The logic is here quite simple. Why does under EHD lubrication where the loads exceed many times the load of HD lubricant, lubricating film remains healthy? When analyzing the friction regularities under EHD lubrication it is necessary to pay attention to the two independent and possible effects. The first one is regularity of plastic deformation (states and properties) at Hertzian contact solids. The second one is the state and properties of the oil film in the condition of irregular and hydrostatic compression.

Let us consider the first. It is deformation of the Hertzian contact. Hertzian contact of friction should be considered as a contact in the most fully developed evolution of plastic deformation. The degree of structural adaptations of such contact can be maximum [12]. In essence, we can have a perfect elasto-visco plastic deformation. Such contact has the maximum capacity for work and temperature effect on contact is minimal. Almost totally equilibrium (rotary elastically, interactive) nano-crystal structures of contact (mechanical quantum [13]) have thermal effect in the form of temperature growth on the temperature level of absolute zero. Such microflash is unable to heat and destroy the oil film. Irrelevance of lubricants is very often supposed for such contacts [11]. But on the other hand the problem of contact temperature cycling and the possibility of gradual heat accumulation requires a lubricant which will take off the heat.

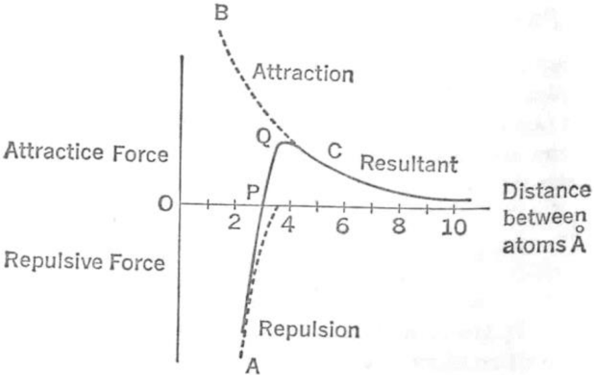

Figure 7: Sketch, showing the way in which the force between two atoms varies with the distance between them.

Thus, despite of the fact that Hertzian contact works at stresses at the threshold of the strength limit, within the contact interaction between structural elements, mechanical quanta, as subtribosystems is realized at the level of the perfect elasticity. Elastic mutual rotations of nanostructures define the essence for models as abnormally low friction and wearlessness [14]. Such state of tribocontact we may examine as state of selforganization, nanoquantum, solid lubricant [15].

Now, as to the second - it is about state and properties of lubricants with EHD lubrication. Quasi solid state of the oil film in full irregular hydrostatic compression can give unique lubrication properties. Firstly, by itself, all round compression taking into account the classic force-separation curve (Fig. 7) interatomic interaction complicates the process of destruction (lubricant state below P point), because for destruction (breaking of atomic bond) stretching is necessary (Q point). Secondly, quasisolid state of oil film may analyze from the perspective of solids friction.

Therefore, the regularities of shear deformation of lubricant (oil) may be similar with regularities that take place under friction of solids, namely, one may remember the structural-energy diagram (Fig. 8) for evolution of the rubbing surfaces [1,2,12,16].

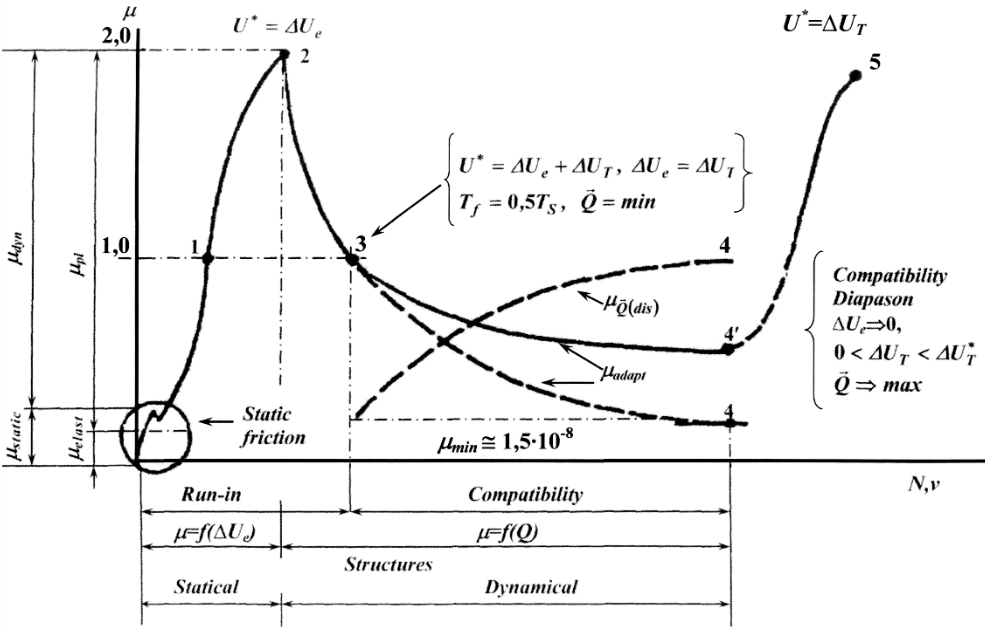

Figure 8: Structural-energy diagram for evolution of rubbing surfaces [1,2,12,16]

Here may well work mechanism for dynamic dissipation of energy with energy balance component $\vec{q}^*$ (Fig. 1), i.e. EHD lubricant can have properties of dissipative structures of friction such by friction of solids. These dissipative structures can be formed at the gap mouth of the expiration of oil where the lubrication hydrostatic compression has irregularity at the expense of stretching (Fig. 9).

Correspondingly, high density of energy flux (friction power) under EHD lubrication stimulates the formation of similar structures of quick heat dissipation.

Here it is quite possible to propose structural model of oil film (Fig. 10) with EHD lubrication in the form of rotary oscillating cells with elastic interactions with each other. This is similar to the Rayleigh-Benard cells in the case of a powerful stationary heating of liquids. It is possible that the size of these cells have an order of about nano-scale level such as fullerene' form or mechanical quantum [12-16]. This corresponds with to the cellular hypothesis of J. Gibbs for case of equilibrium and reversible process. Accordingly, this oil film has maximum dissipative properties.

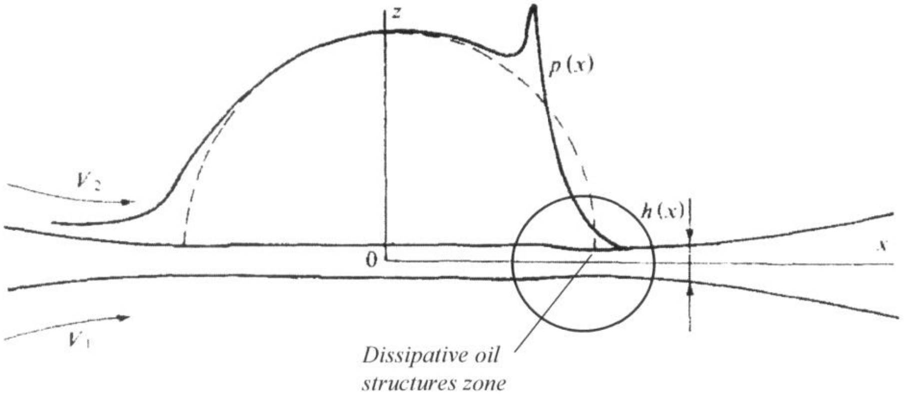

Figure 9: Dissipative oil structures zone under EHD lubrication

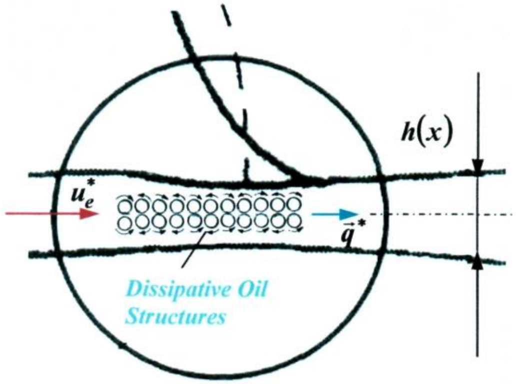

Figure10: Cellular (nano-structured) model of EHD lubricant into a narrow gap between two surfaces.

These high structured oil films dissipate energy in the direction of relative motion of bodies. Here all accumulated energy Δu_e^* in compressed zone (the work of external forces) is almost entirely scattered by the dissipative structures of oil film.

6. Conclusion

Thus, neither the first nor the second effects Hertzian contact do not give the temperature effect of friction. When EHD lubrication there is we have no temperature effect for destruction of lubricant. The criterion of the ultimate state of oil film in EHD is a critical density $\vec{q}^*$ of dissipation energy, which is equal to the critical density of the internal thermal energy u_T^* lubricant.

The concept of temperature for such film has almost no meaning. Here you should write ratio

$$\Delta u_T = u_T^* - u_{T0} = 0 \,. \tag{23}$$

This is associated with a particular (unique) structural state of the oil film. The presence of dissipative component $\vec{q}^*$ presupposes the equality to zero condition of temperature flashes $\Delta u_T = 0$ and $\Delta T = 0$. Therefore, achieving the critical state of the film cannot be until the dissipative structures lubricating film is operative.

Loadability of EHD lubrication film is very high precisely because of the elastic and reversible energy dissipation. As a result, we can write the following - the equations for critical power of friction for HD and EHD lubricants:

$$\dot{W}_{HD} = \dot{V}\Delta u_T^* = \dot{V}\rho\, c_p (T^* - T_0) \,. \tag{24}$$

$$\dot{W}_{EHD} = \dot{V} \cdot \vec{q}^* \,. \tag{25}$$

Here $\dot{V}$ is the amount of lubricant in contact at a time. This result is fully in line with the practice.

EHD lubrication capacity for work should be significantly higher than HD lubrication:

$$\dot{W}_{EHD} >> \dot{W}_{HD} \,, \tag{26}$$

because

$$\vec{q}^* >> \Delta u_T^* \,. \tag{27}$$

If you write the numerical values Δu_T^* and $\vec{q}^*$ for engine oil, for example, M14V (Table 3) then we get the following experimental results for AlSn20 and CuPb30 (in brackets): $\Delta u_T{}^* = 43(54)\,\mathrm{MJ}/m^3$, and $\vec{q}^* = u_T^* = 725(727)\,\mathrm{MJ}/m^3$.

In the most general case, the thermal model of the ultimate state of oil film with HD and EHD lubricants are of the form:

HD lubricant - $\dot{W}_{HD} = \dot{V}q^*$, here $q^* = \Delta u_T^*$, and $\vec{q}^* = 0$; (28)

EHD lubricant - $\dot{W}_{EHD} = \dot{V}q^*$, here $q^* = \vec{q}^* = u_T^*$, and $\Delta u_T^* = 0$. (29)

Excess of specific friction power above critical level would lead to turbulence of the flow, laminar flow destruction of dissipative structures and consequently to loss of load capacity of EHD. It will be a critical state.

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