Evaluation technique of oils tribotechnical characteristics on the basis of their rheological and antifriction properties determination under the conditions of rolling motion and rolling with slipping

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Abstract
Change of thickness of a lubricant layer depending on rolling speed is investigated. Quantitative indicators of friction coefficient, effective viscosity, shear rate are experimentally defined. It is established that in the conditions of pure rolling and rolling with slip at flood lubrication with a growth of rolling speed there is an increase of thickness of a lubricant layer in the central contact zone.
Key words: LUBRICANT MODE, VISCOSITY, ROLLING BEARING, TRIBOTECHNICAL CHARACTERISTICS, LUBRICATING OIL

The influence of rolling motion rate on lubricant layer thickness is one of the main aspects of elastohydrodynamic (EHD) lubricant of pointed contact. The thickness change of lubricant layer depending on rolling motion rate allows revealing of influence of rheological features of lubricants wide range on operating capability of rolling bearings. The condition of pure rolling is necessary for avoiding of lubricant temperature increase and further viscosity reduction in input as a result energy dissipation connected with slipping due to viscous friction. In order to guarantee the pure rolling condition (when surface velocities are equal), the ratio $V_1 = V_2$ must be realized in the following expression for ball-and-disk contact:

$$V_1 - V_2 = \frac{2\pi}{60} \cdot (\omega_1 \cdot r_1 - \omega_2 \cdot r_2), \qquad (1)$$

where V_1, V_2 - linear velocity of friction couple (ball and disk); r_1, r_2 – radiuses of ball and disk; ω_1 and ω_2 - angular velocity of ball and disk.

In order to fulfill the condition of pure rolling, it is necessary for the ratio $\omega_1 = 3\omega_2$ to be realized; that is, it is necessary for the angular velocity of ball to exceed the angular velocity of disk by 3 times, in this case, the expression (1) will be of the form:

$$r_2 = 3r_1.$$

Consequently, for providing of pure rolling condition, it is important for the ball to from the center of disk rotation at distance, which is three times larger than its own radius.

The pure rolling is necessary for avoiding of lubricant temperature increase and further viscosity reduction in input to contact as a result energy dissipation connected with slipping due to viscous friction.

Rolling with slipping rate is measured directly by shift of ball contact zone with disk at a distance of r_d>38.1 mm; that is, the distance, where pure rolling was being observed, was exceeded.

By means of the sensor of electronic tachometer TTs-ZM, which records the number of turns, the optical and actual thickness of lubricant layer and dimensionless parameter λ are determined. Parameter λ is lubrication mode and is determined by a formula:

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$$\lambda = \frac{h}{\sqrt{R_{a1}^2 + R_{a2}^2}}, \qquad (2)$$

where h - thickness of lubricant layer, micron;

R_{a1} – glass disk surface average roughness, micron;

R_{a2} – steel ball (roller) surface average roughness, micron.

According to value λ, the classification of lubrication modes is the following:

λ= 0 – 1 – semidry;

λ= 1– 1,5 – boundary;

λ= 1,5 – 3 – mixed with predominance of boundary;

λ= 3 – 4 – elastohydrodynamic;

λ≥ 4 – hydrodynamic lubrication mode in the contact.

In order to characterize the properties of lubricants, which are used for friction surfaces lubrication, it is necessary to investigate their rheological parameters in a contact zone. Simultaneous change of lubricant layer thickness and friction force allows determining of rheological characteristics and viscosity directly within friction contact [1, 4].

According to EHD-theory of lubrication, viscosity is an important factor in course of lubricants investigation, as it is one of the main indicators of oils physical properties. Technical state of tribotechnical systems, consumption of fuel, electric power of system engines (ICE, electric motors) depend on lubricant viscosity. According to viscous indicators, lubricant for the corresponding friction unit is selected depending on its design, technical state, operating conditions, season and other factors [2].

Rheological curves are dependence of shearing stress of lubricant layer τ on shearing rate gradient γ [3]. The shearing rate gradient is the ratio of difference of contact surfaces velocity to lubricant layer thickness.

Average value of shearing rate gradient in oil layer for each experimental point of rheological curve is determined by formula:

$$\gamma_i = \frac{V_{sl}}{h_t}, \qquad (3)$$

where $V_{sl} = V_d - V_b$ — sliding velocity of the contact bodies, m/s;

V_d – disk rolling rate, m/s;

V_b – ball rolling rate , m/s;

h_t – true thickness of lubricant layer, m.

Average value of shearing stress in contact is determined by formula:

$$\tau_i = \frac{2M_i}{D \cdot S}, \qquad (4)$$

where M_i - frictional moment – Hmm;

D – diameter of experimental ball, mm;

S - area of pressure zone in the oil layer accepted as equal to the area of contact according to Hertz, mm^2.

Effective lubricant viscosity in a contact zone is determined by formula:

$$\eta_{ef} = \frac{\tau_i}{\gamma_i} \qquad (5)$$

Establishment of dependences is presented in the following sequence:

1. Dependence of thickness (h_t) on rolling rate (V_{rol})

Table 1. Operational parameters of a friction pair and calibrating dependences of optical and valid thickness of a lubricant layer

No	n, r/m$_i$n	Color	Optical thickness h_o * 10-6, m	True thickness h_t * 10-6 m	Rolling motion rate, V_{rol}	λ
1	4	1st yellow	0,192	0,1306122	0,024	0,923568
2	7	1st orange	0,2025	0,1377551	0,042	0,9740757
3	8	1st violet	0,2835	0,1928571	0,048	1,3637059
4	9	1st blue	0,354	0,2408163	0,054	1,7028286
5	10	1st green	0,3975	0,2704082	0,06	1,9120745
6	14	2nd yellow	0,411	0,2795918	0,084	1,9770128
7	17	2nd light red	0,465	0,3163265	0,102	2,2367663
8	18	2nd purple	0,534	0,3632653	0,108	2,5686736
9	18,5	2nd indigo	0,561	0,3816327	0,111	2,6985504
10	20	2nd blue	0,594	0,4040816	0,12	2,8572886
11	21	2nd green	0,6375	0,4336735	0,126	3,0665345
12	23	3rd yellow	0,69	0,4693878	0,138	3,3190726
13	25	3rd red	0,735	0,5	0,15	3,5355339
14	27	3rd green	0,9	0,6122449	0,162	4,3292252

Note: V_{rol} = (0.36*n)/60, m/s
0.36-coefficient
60- seconds

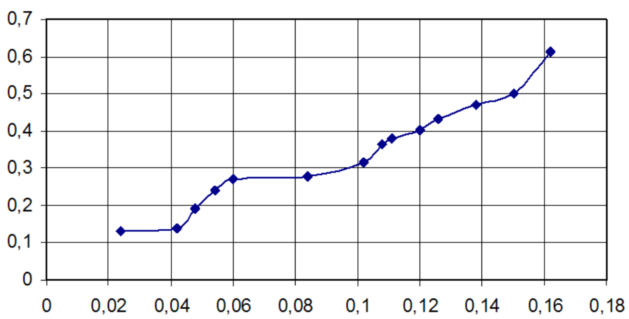

Figure 1. Dependence of oil layer thickness on rolling motion rate

2. Effective viscosity in a contact zone

$\eta_i = \tau_i / \gamma'$, [MPa·s]

3. Average value of shearing stress in contact (τ_i)

$\tau_i = 2M_i / D \cdot S$, [MPa]

where M_i - frictional moment caused by slipping

$M_i = f_{fric} / 0.021$

$f_{fric} = M_i / r \cdot N$ - friction coefficient

D - diameter of sample (ball), mm D =25.4

S - the area of pressure zone in a lubricant layer, m^2 S = π·ρ^2; π =3.14

ρ - radius of the contact area ρ = 0.909 · 3^√ θΣ·r·N

θΣ = θ1 + θ2 - elastic constant of material for two deformed bodies, [m^2 / H]

$\theta 1$ - steel $\theta 1 = (1-\mu\text{^}2) / E = (1-\nu\text{^}2) / E$

$\theta 2$ - glass $\theta 2 = (1-\mu\text{^}2) / E = (1-\nu\text{^}2) / E$

$\theta 1 = (1-\mu\text{^}2) / E = (1-\nu\text{^}2) / E = (1-0{,}3\text{^}2) / (2{,}07{*}10\text{^}11) = 0.44\cdot 10\text{^-}11$; $\theta 1 = 4.39614E\text{-}12\ m^2 / H$

$\theta 2 = (1-\mu\text{^}2) / E = (1-\nu\text{^}2) / E = (1-0.25\text{^}2) / (0.757{*}10\text{^}11) = 1.24\cdot 10\text{^-}11$; $\theta 2 = 1.23844E\text{-}11 m^2 / H$

$\theta\Sigma = \theta 1 + \theta 2 = 0.44\cdot 10\text{^-}11 + 1.24\cdot 10\text{^-}11 = 1.68\cdot 10\text{^-}11$, $[m\text{^}2 / H]$; $\theta\Sigma = 1.67805E\text{-}11\ m^2 / H$

r – ball radius, m; $r = 12.7\cdot 10^{-3}$

N - normal component of loading (one load weight); N = 15 kgf·cm

Therefore:

$\rho = 0.909 \cdot 3\text{^} \sqrt{}(1.68\cdot 10\text{^-}11 * 12.7\cdot 10\text{^-}3 * 3.75) = 8.4\cdot 10\text{^-}6$; $\rho = 8.44E\text{-}05$ m

$S = 3.14 * (8.4{*}10\text{^-}6)\ \text{^}\ 2 = 22.3\cdot 10\text{^-}6$, mm^2; $S = 2.23E\text{-}08\ m^2$

4. The average value of shearing gradient of lubricant layer (γ ‘)

$\gamma' = V_{sl} / h_t$, [s-1]

$V_{sl} \approx 1\% V_{rol}$

5. Lubrication mode

$\lambda = h_t / \sqrt{}(R_{a1}{}^2 + R_{a2}{}^2)$

Table 2. Dynamics of tribotechnical characteristics of lubricating oil

No	Rolling motion rate V_{rol}, m/s	Effective viscosity η_i, MPa·s	Frictional moment M_i, H·mm	The average value of shearing stress τ_i, [MPa]	The average value of shearing gradient γ', s-1	Friction coefficient f_{fric}	Slipping rate V_{sl}, m/s	True thickness h_t * 10-6
1	0,024	2,47E+05	0,128571	4,53E+02	0,0018375	0,0027	0,00024	0,1306122
2	0,042	1,32E+05	0,114286	4,03E+02	0,00304889	0,0024	0,00042	0,1377551
3	0,048	1,58E+05	0,111905	3,94E+02	0,00248889	0,00235	0,00048	0,1928571
4	0,054	1,72E+05	0,109524	3,86E+02	0,00224237	0,0023	0,00054	0,2408163
5	0,06	1,66E+05	0,104762	3,69E+02	0,00221887	0,0022	0,0006	0,2704082
6	0,084	1,20E+05	0,102381	3,61E+02	0,00300438	0,00215	0,00084	0,2795918
7	0,102	1,10E+05	0,100476	3,54E+02	0,00322452	0,00211	0,00102	0,3163265
8	0,108	1,18E+05	0,099524	3,51E+02	0,00297303	0,00209	0,00108	0,3632653
9	0,111	1,19E+05	0,098095	3,46E+02	0,00290856	0,00206	0,00111	0,3816327
10	0,12	1,15E+05	0,096667	3,41E+02	0,0029697	0,00203	0,0012	0,4040816
11	0,126	1,16E+05	0,095238	3,36E+02	0,00290541	0,002	0,00126	0,4336735
12	0,138	1,12E+05	0,093333	3,29E+02	0,00294	0,00196	0,00138	0,4693878
13	0,15	1,06E+05	0,090476	3,19E+02	0,003	0,0019	0,0015	0,5
14	0,162	1,14E+05	0,085714	3,02E+02	0,002646	0,0018	0,00162	0,6122449

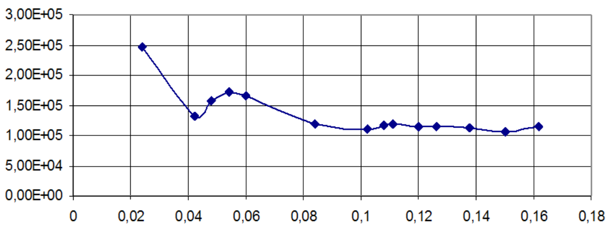

Figure 2. The dependence of effective viscosity on rolling rate

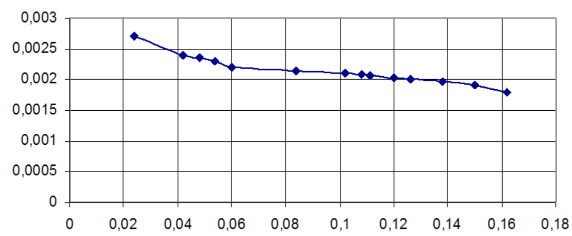

Figure 3. The dependence of friction coefficient on rolling rate

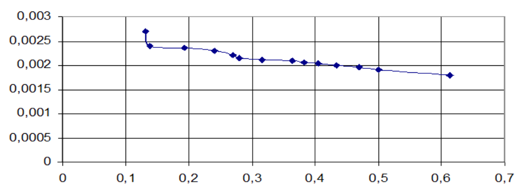

Figure 4. The dependence of friction coefficient on true thickness of lubricant layer

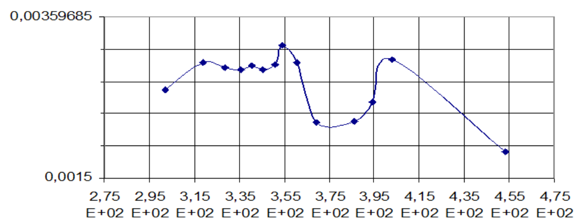

Figure 5. The dependence of shearing gradient on shearing stress

6. Maximum pressure in contact (P_{max})

$P_{max} = 0.578 * \sqrt[3]{(N/(Q\Sigma^2 * r^2))} = 251689461$ H/m²

Sinking depth

$h = 0.825 * \sqrt[3]{((Q\Sigma * N^2)/r)} = 0.0021851$ H*m

Conclusions

Thus, on the basis of the presented dependences it is established that with a growth of rolling motion rate, the thickness of lubricant layer in the central zone of contact is increased under the conditions of pure rolling and rolling with slipping in case of plentiful lubrication independently of oil composition. This provides the transition from boundary to hydrodynamic lubrication mode.

When pure rolling, the formation kinetics of lubricant layer thickness depends on oil viscosity, mineral or synthetic components, additives, as well as on contact surfaces type. If there is slipping, the oil film formation mechanism depends on oil components resistance to gradient of shearing rate, which tends to continuous growth.

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