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The effect of dispersion of dirt particles in oils on their electrical conductivity and mechanical strength

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Abstract

It has been shown theoretically and confirmed experimentally that the dispersion of dirt particles found in engine oils and working fluids affects significantly their physical properties. In particular, it has been established that if dirt particles are artificially dispersed in a lubricant, its electrical conductivity increases. This, in turn, is expected to lead to a decrease in the share of electrostatic wear of the tribo units. Such particles are also able to increase the mechanical strength (surface tension) of lubricating films, that is, to make the boundary layers more durable, due to which we can expect a decrease in wear of tribo units. In this case, the thermal conductivity of oil lubricating films with highly dispersed dirt particles does not change.

Key words: dispersion; dirt particles; wear; electrical conductivity; lubricants; thermal conductivity.

Introduction

As is known, during the operation of engine oils and working fluids, dirt particles are accumulated in them due to wear of tribo surfaces. These particles have a certain effect on the process of friction and wear [1–4]. At the same time, the dispersity of dirt particles plays a significant role [4–6]. In addition, there is an assumption that the size of these particles affects significantly some of the physical properties of lubricants, however there are no theoretical concepts in the literature that confirm this relationship.

Main heading

Determining the effect of dispersion of dirt particles on the electrical conductivity, mechanical strength, and thermal conductivity of lubricants.

Presentation of research materials

It should be assumed that the electrical conductivity of a suspension formed by metal particles of wear in the oil must have an activation mechanism. With a small concentration of the impurity phase, this mechanism is mainly provided by the transfer of electrons between individual particles by means of thermionic emission [7, 8].

Let some volume of the suspension have an initial surface area of oil S_0, particles S_0' and surface tension, respectively, α and α'.

We will consider the case when the particles are artificially dispersed by a special device (hydrodispersing agent [9]). The area of such particles S_k' after dispersion will be equal to:

$$S_k' = S_0' + 2(K-1)\cdot\frac{S_0'}{\gamma'}, \qquad (1)$$

where K – is a coefficient equal to the ratio of the number of particles after dispersion to the initial number of particles;

γ' – is the factor of area conversion.

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As is known, activated conductivity σ is determined from expression [10]:

$$\sigma = \sigma_0 \cdot \exp\left(-\frac{E}{K_B \cdot T}\right), \tag{2}$$

where σ_0 – is the constant depending on the individual properties of the suspension;
E – is the energy of activation;
K_B – is the Boltzmann constant; T is the temperature.

The constant σ_0 that formally has the physical meaning of electrical conductivity at an infinitely high temperature can be determined from the expression:

$$\sigma_0 = \frac{n_0 \cdot e^2 \cdot \tau}{m}, \tag{3}$$

where n_0 – is the concentration of electrons;
e – is the electron charge;
τ – is the time of the electron free run;
m – is the electron mass.

It is obvious that the concentration of the emitted electrons is proportional to S_k', that is:

$$\eta_k = B \cdot S_k', \tag{4}$$

where B – is the coefficient of proportionality.
Then:

$$\sigma = B \cdot S_k' \cdot \frac{e^2 \cdot \tau}{m} \cdot \exp\left(-\frac{E}{K_B \cdot T}\right). \tag{5}$$

Substituting (1) into (5), we finally receive:

$$\sigma_k = B \cdot S_0' \cdot \left[\frac{2(k-1)}{\gamma'} + 1\right] \cdot \frac{e^2 \cdot \tau}{m} \cdot \exp\left(-\frac{E}{K_B T}\right). \tag{6}$$

As follows from (6), with other things being equal, σ_k depends linearly only on the value of the coefficient K, with whose increase the electrical conductivity of the oil film increases.

To receive the equation for the surface tension of the suspension after dispersion, let us estimate the area of the ground particles in the free surface of the oil film. To do this, we introduce the value γ_s equal to the ratio S_k' to the volume V of the oil film:

$$\gamma_s = \frac{S_k'}{V}.$$

Let us consider the volume of the film $\Delta V = S_0 \cdot \Delta h$, where Δh is the distance between two adjacent layers in which the particles are located. It is obvious, that Δh is the thickness of the layer with no particles inside it, while they can be found on the surface.

The area of such particles is equal to:

$$S'_{K_{пов}} = \gamma_S \cdot \Delta V = \gamma_S \cdot S_0 \cdot \Delta h.$$

It is obvious that:

$$\Delta h = \sqrt[-3]{n'_K}\ ,$$

where n'_K – is the concentration of dispersed particles related to their initial concentration n'_0 by the ratio $n'_K = K \cdot n'_0$.

Then

$$S'_{K_{\text{пов}}} = \gamma_S \cdot S_0 \cdot \sqrt[-3]{n'_K}\ .$$

The area of dispersed particles on the surface of the oil film will be:

$$S'_{K_{\text{пов}}} = \frac{S'_K}{V} \cdot S_0 \cdot \sqrt[-3]{K \cdot n'_0} = \frac{S'_0 + 2(K-1) \cdot S'_0 / \gamma'}{V} \cdot S_0 \cdot \sqrt[-3]{K \cdot n'_0}$$

The expression for the surface tension of the suspension containing dispersed particles will be:

$$\alpha_K = \frac{\alpha\left(S_0 - S'_{K_{\text{пов}}}\right) + \alpha' \cdot S'_{K_{\text{пов}}}}{S_0}. \tag{8}$$

Substituting the value $S'_{K_{\text{пов}}}$ from (7) into (8) we receive:

$$\alpha_K = \alpha + \frac{\alpha' - \alpha}{V \cdot \gamma' \cdot \sqrt[3]{K \cdot n'_0}} \cdot S_0 \cdot \left(2K - 2 - \gamma'\right). \tag{9}$$

With sufficiently large values of K, expression (9) takes the form:

$$\alpha_K = \alpha + \frac{2 \cdot (\alpha' - \alpha) \cdot S_0 \cdot K^{2/3}}{V \cdot \gamma' \cdot \sqrt[3]{n'_0}}. \tag{10}$$

As it follows from expression (10), with an increase in the number (decrease in size) of particles due to dispersion, the surface tension (mechanical strength) of the suspension increases. That is, it can be assumed that highly dispersed dirt particles contribute to the greater resistance of the boundary lubricating film.

We can also arrive at the conclusion that the surface tension increases as the system approaches a stationary state, based on the considerations of thermodynamics. Thus, in accordance with the Gibbs-Helmholtz equation for the surface layer of a liquid [11]:

$$U_A = \alpha - T\left(\frac{\partial \alpha}{\partial T}\right),$$

where U_A – is the surface density of internal energy;

α – is the surface density of internal energy (surface tension);

$-\dfrac{\partial \alpha}{\partial T} = S_A$ – is the surface density of energy $\left(S_A\right) > 0$.

If the surface tension α depends on the number N of wear particles in the oil, which, in turn, depends on the time t of the system staying in an unsteady state, then:

$$\frac{\partial \alpha}{\partial T} = \frac{d\alpha}{dN} \cdot \frac{dN}{dt} \cdot \frac{dt}{dT}\ .$$

On the basis of the Prigogine theorem when approaching a stationary state:

$$\frac{dT}{dt} < 0$$

Since $\frac{\partial\alpha}{\partial T} < 0$, then it should be:

$$\frac{d\alpha}{dN}\cdot\frac{dN}{dt} > 0 .$$

Due to the fact that in the process of running-in and as a result of artificial dispersion, an increase in the number of particles occurs, $\frac{dN}{dt} > 0$. Consequently, $\frac{d\alpha}{dN} > 0$.

Hence, with approaching a stationary state, the surface tension of the oil containing wear particles should increase as their number increases.

It should be noted that inequality $\frac{d\alpha}{dN}\cdot\frac{dN}{dt} > 0$ can be satisfied provided $\frac{dN}{dt} < 0$ and $\frac{d\alpha}{dN} < 0$. These conditions, obviously, describe the removal of dispersed particles from the oil in the absence of wetting, which leads to a decrease in the surface tension that does not wet the particles in it.

If we take $K = I$ (there is no artificial dispersion), then, as follows from formulas (6) and (10), the electrical conductivity σ_1 and the surface tension α_1 of the suspension will be smaller, respectively σ_κ and α_κ.

If we put $S_0' = 0$ (the oil completely purified from particles) into (6) and (10), then we receive $\sigma_0 = 0$, and $\alpha_0 = \alpha$. Thus, the oil without particles does not theoretically conduct electricity, and the surface tension α_0 is smaller than α_1 and α_κ.

Therefore, the following inequalities are true:

$$\sigma_0 < \sigma_1 < \sigma_K ; \tag{11}$$

$$\alpha_0 < \alpha_1 < \alpha_K . \tag{12}$$

To verify the proposed theoretical principles experimentally, laboratory studies were conducted to establish the electrical conductivity of the M-12-G$_2$ motor oil, which was available in the following conditions: fresh, working in the engine for 120 machine-hours, and the same working oil after pollution particles had been artificially dispersed in it.

The studies were carried out on a special laboratory plant (the measurement block diagram is shown in Fig. 1) using a K-6 benchtop micrometer with a pointer reading device with a scale division of 1 μm. As a power source, the ЗГ-33 generator was used. In this case, the applied voltage was carefully stabilized. The electrical resistance, as a function of the oil film thickness, was estimated by the extreme points of the current-voltage characteristics in arbitrary units at constant values of the vertical and horizontal scanning of the SDS5032X oscilloscope.

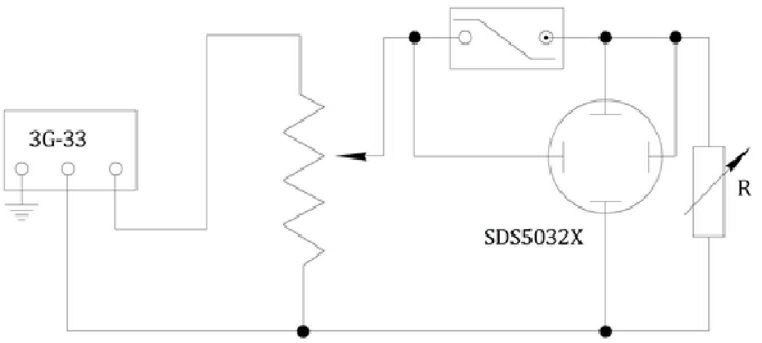

Fig. 1. Block diagram of the oil film electrical resistance measurement

The experimental technique implied that the micrometer needle was set to 0, then the indicator tips were moved apart by 30 μm, and a drop of oil was applied to the gap, after which the tips were reduced and the oil was squeezed out of the gap under the action of the indicator spring. A voltage was applied to the tips (plates), and the current-voltage characteristic and the coordinates of its extreme points were recorded on the oscilloscope screen. To determine the value of R, the values of voltage and current were estimated on the oscilloscope screen. The interval of measurements was 0.5 μm.

The results of the research (Fig. 2) showed that the electrical resistance R of the fresh oil (curve 1) was greater than that of the working oil (curve 2). In turn, the electrical resistance of the oil after artificial dispersion of pollution particles in it (curve 3) was less (the electrical conductivity was greater) than that of the working one. For example, with a film thickness of 3 μm, R of the fresh oil was 1.44 (in arbitrary units), of the working one was 1.12 (1.3 times less than that of the fresh one) and of the used one was 0.72 (1.5 times less than that of the working oil).

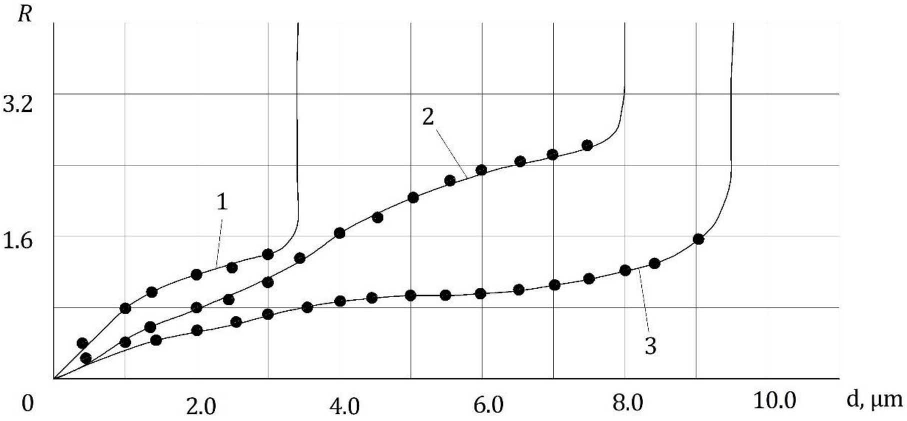

Fig. 2. The dependence of the electrical resistance of the oil film on its thickness (M-12-G$_2$ oil):
1 – fresh oil;
2 – working oil;
3 – working oil after artificial dispersion of pollution particles

With large thicknesses of the film, the difference in electrical resistance is even more significant.

Thus, by the increase of electrical conductivity (decrease of resistance), the oils are arranged in a row: fresh, working, working after artificial dispersion of the pollution particles in it, i.e., the validity of the in equation was experimentally confirmed (11).

In addition, it can be seen from Fig. 2 that the maximum thickness of the film α_{max}, depending on the surface tension, at which it still has conductivity, is 3 μm for the fresh oil and 7.5 μm for the operating oil (2.5 times greater than that for the fresh oil), for the artificially dispersed oil it makes up 9 μm (1.2 times greater than that for the working oil), which validated the in equation (12).

According to the method developed by us, studies were also conducted to determine the surface tension of I-G-A-32 oil, which was available in the following conditions: fresh, fresh with pollution particles from 38XC steel at a concentration of 0.1 % by weight artificially introduced into it, and the same oil after artificial dispersion of pollution particles in it. To study the surface tension, a standard burette was used, into which the test oil was poured. A drop of oil flowing from the nose of the burette was observed using a lens with a magnification of x24 and a scale division of 0.1 mm.

The methodology of the research assumed the determining of the diameter of the drop neck at the moment of its separation and the establishing of the mass of one drop by weighing a dry bunsen beaker on a VLT-1 laboratory balance and the same bunsen beaker after 100 drops of the test oil had been dripped into it.

Table 1

The surface tension of I-G-A-32 oil

Oil condition	α, mN/m
Fresh	29.6
Fresh with metal particles of 38 XC steel	32.5
Fresh with the dispersed particles of 38XC steel	35.4

Note: The table shows the average values for the results of four tests on each oil.

The value of the surface tension α was determined by the formula:

$$\alpha = \frac{m\cdot g}{\pi\cdot d_o}, \tag{13}$$

where m – is the mass of the drop;

d_o – is the diameter of neck of the drop at the moment of its separation;

g – is the gravitational acceleration.

To obtain the reliable results, experiments on each oil were repeated 4 times, which, according to the preliminary studies, allowed to obtain a relative error of not more than 0.05 with a confidence factor of 0.9.

As follows from the data in Table 1, IG-A-32 oil has the highest surface tension after pollution particles have been artificially dispersed in it. This means that with the boundary friction, the rupture of the oil film occurs at its relatively large thicknesses. This, in turn, will lead to the fact that the transition of the film to a non-conductive state will occur later in comparison with this oil in its first two conditions, that is, a high dispersion of pollution particles should lead to a decrease in electrostatic wear.

Conclusion

As a result of the foregoing, the dispersion of wear particles of metal surfaces affects both the electrical conductivity and the mechanical strength, but practically does not affect the thermal conductivity of the oil.

Similarly, such dirt particles lead to an increase in the surface tension (mechanical strength) of the oil film, which can cause an increase in its thickness, at which the film breaks, that is, it is transformed into a non-conductive state. The increasing of the surface tension should also reduce the electrostatic component of wear.

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Венцель Є.С., Щукін О.В., Орел О.В., Саєнко Н.В., Євтушенко А.В. Вплив дисперсності частинок забруднень у мастилах на їх електропровідність і механічну міцність.

Теоретичним шляхом показано і експериментально підтверджено, що дисперсність частинок забруднень, які знаходяться в моторних мастилах і робочих рідинах, істотно впливає на їх фізичні властивості. Так зокрема, встановлено, що якщо штучно диспергувати частинки забруднень в змащувальному матеріалі, то його електропровідність зростає. Це, в свою чергу, має призвести до зниження частки електростатичного зношування трибовузлів. Також такі частинки здатні збільшити механічну міцність (поверхневий натяг) мастильних плівок, тобто зробити граничні шари більш міцними, за рахунок чого можна очікувати зменшення зносу трибовузлів. При цьому теплопровідність мастильних змащувальних плівок з високодисперсними частинками забруднень не змінюється.

Ключові слова: дисперсність, частинки забруднень, зношування, електропровідність, змащувальні матеріали, теплопровідність.