Tribological activity of ultradisperse organic lubricant additives for cam mechanisms subject to abrasive wear

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Abstract. The effect of nanodispersed triboactive additive introducing into the oil suspension of model abrasive is considered. The influence of the concentrations both additive and abrasive, as well as the dispersion of the solid phase on the wear of steel-steel pair friction, is determined. It has been suggested that carbon nano-particle additives under these conditions can shield the level of abrasive wear.

1. Introduction
Cam mechanisms which are suffering from abrasive wear and those mechanisms are widely used in automatic machines of textile, publishing and light industry.

A change in the geometry of the profile of a cam mechanism due to wear leads to blows (changes in acceleration) that destroy the contact surfaces of the cam and the pusher. In many respects, the wear resistance of the cam mechanism depends on the value of contact stresses, the quantitative characteristic in the contact is the calculation of the contact strength of cams and rollers according to the Hertz-Belyaev formula. In this regard, it is important to take into account the contamination of lubricant with abrasive particles.

Many studies on the behavior of abrasive particles in the lubricant are devoted to (see, for example, [1-3]). They consider abrasive wear models under conditions of liquid-flowing, plastic lubricants or without lubrication. In recent years, the study of nanodisperse additives in tribology as systems with high specific surface area has been actively developed. The application of additives based on carbon nanoparticles (in the form of allotropic carbon modifications: single-wall and multi-wall carbon nanotubes, graphene and graphene oxide, schungite nanoparticles) has attracted increased interest in recent decades [4-8]. Multi-Wall Carbon Nanotubes (MWCN), which is an allotropic modification of carbon that has a cylindrical structure with a diameter of up to tens of nanometers and length from 1 µm to several centimeters, is of interest among researchers [8-13] due to the ability to improve tribological characteristics of lubricants and to form a film on the friction surfaces that reduces the wear and tear of parts. An important characteristic that distinguishes MWCN from other carbon nanomaterials is their high hardness [14].
Purpose of following research is:
- to check influence of MWCN as systems with higher hardness among all other carbon allotropic modifications;
- to find connection of its molecular structure with non-abrasive action.

2. Materials and methods
As an oil material was used oil I-40A (Russian standart 20799-88, analogue of BP Energol CS 32).
As an active abrasive agent of oil material was injected abrasive material- Electrocorundum 25A 0.063-0.125 (F180) (Russian standart28818—90,analogue of White fused aluminium oxide(corundum) EK). Main characteristics of Corundum are in table1 and figure 1.

| Characteristic                     | Corundum 25A (F180) |
|-----------------------------------|---------------------|
| Fraction composition, nm          | 0.063-0.125         |
| Main size of fraction, nm         | 0.075-0.090         |
| Content of $\text{Al}_2\text{O}_3$ | 96-99%              |
| Microhardness, GPa                | 19.6-20.9           |
| Density, g·cm$^{-3}$               | 3.9-3.95            |

![Figure 1. Characteristic shape of abrasive corundum particles.](image)

As an additive is was used carbon nanotubes Taunit-M (produced by «NanoTechCenter Co., LTD», Tambov city).Carbon nanotubes (UNT) line «Taunits» - quasi one-dimensional, nanoscale, filamentous formations of polycrystalline graphite with mostly cylinder form with inner channel (table 2).

| Characteristic | Taunit-M |
|----------------|----------|
| Internal diameter, nm | 10-30 |
| Internal diameter, nm | 5-15  |
| Length, $\mu$m | $\geq$2 |
| Specific surface, m$^2$·g$^{-1}$ | $\geq$270 |

![Table 2. Characteristics of MWNT Taunit-M.](image)

Abrasive agent and UNT additive were injected into Oil Material (OM) by mechanical mixing and followed ultrasonic dispersion. Tribologic tests were made at universal friction machine MTU-01 (TS 4271-001-29034600-2004). Rotational speed of shaft kept constant – 200 rpm. As a friction pair were used 3 balls with diameter 12.7 mm, steel ShKh15 – analogue of AISI Steel 52100, hardness 60-62
HRC (Russian Standard 3722-2014) and steel plate, steel R6M5 - analogue of AISI M2 HSS (Ra 1.25 µm, hardness 65 HRC). Scheme of the device is on figure 2.

Figure 2. Geometric parameters of the friction pair.

The wear scar diameter measured on a microscope Biolam-M with digital camera Levenhuk M500 Base, using the software ToupView.

3. Results of the experiment and their discussion

3.1. Theoretical model

During the process of abrasive wear of shaft, it will be checked geometry of contact. Let’s consider following situation.

\[ S – \text{an area of contact, } n – \text{number of particles of abrasive agent, effected to this area, } l = v \cdot t – \text{glide way, passed during time } t \text{ with velocity } v. \text{ Surface wear will be both from cam and from pusher roller. We accept, that area is function of time } S = S(t). \]

If we talk about cam mechanism of textile machine (e.g., in sealed box), vertical force \( F \) will be changed according to the periodic law

\[ F = b \sin^2 \omega t, \]

Where \( b \) – coefficient of proportionality, \( \omega \) – frequency of interaction in the sliding friction mode. Constant \( b \) and frequency \( \omega \) are determined based on the geometry of the friction pair.

Let’s enter: \( P(S_n) \) – probability, that with \( P_0 = \frac{F}{S} \) pressure and velocity \( v \) a wear particle will appear.

Thus, the number of wear particles \( N_w \) will increase over time

\[ N_w(t) = P \cdot N_k(t) \quad (1) \]

\( N_k \) – is a number of abrasive material additives during the way \( l \).

In case if, cam mechanism wear will be more, than pusher roller wear, number of abrasive particles \( n_k \), per unit run length, that

\[ N_k(t) = n_k l = n_k vt \quad (2) \]

And the number of wear particles

\[ N_w(t) = P \cdot n_k vt \quad (3) \]

In this case, the assumed probability model is
\[ P = e^{-\alpha \frac{A}{n}} \]  

(4)

where \( \alpha \) -the ratio of the material hardness to the hardness of the abrasive particles, what characterizes their cutting ability, \( A_n \) - work of normal forces, \( A_t \) - work of tangential forces, which depends on the parameters of the lubricant oil, temperature, abrasive particles geometry.

In this case, wear rate \( I_w \) of the mating part of the part (cam mechanism) - \( I_w = \frac{dN_k(t)}{dt} = Pn_k\nu \) equilibrium value of surface wear at a given speed. Wear particles have a shielding effect on the entrance and exit of the friction zone of corundum particles, fixing the concentration.

When both parts of the friction pair wear out

\[ n_k = n_k(t) \]  

Then

\[ N_w^{i} = P^{i}n_k(t)\nu t \]  

(6)

And wear speed

\[ I_w^{i} = \frac{dN_w^{i}(t)}{dt} = P^{i}\nu \frac{dn_k(t)\cdot t}{dt} \]  

(7)

When using the model in practice, to work correctly, you need to define \( n_k(t) \) for a specific friction unit, which depends on the geometry of the friction pair (in particular, the cam mechanism). Then the dependence of the number of wear particles on time takes the form:

\[ n_k = \frac{\alpha}{2} t + n_k(0) \]  

(8)

In this case, the wear rate is set by the expression.

\[ I_w^{i} = \frac{dN_w^{i}(t)}{dt} = P^{i}\nu \frac{d}{dt}\left( \frac{\alpha}{2} t^2 + n_k(0)t \right) = P^{i}\nu(n_k(0) + \alpha t) \]  

(9)

If additives dispersed to nanoscale are additionally introduced into the system, which are able to bind to abrasive particles, they will, first of all, have a screening effect on the particles of the abrasive material, thereby reducing their cutting effect, and, consequently, reducing the ratio in the constant of compliance to wear.

In the process of abrasive wear, in addition to the initial particles of the abrasive material, wear particles of the friction surfaces will also be formed, which are metal oxides that have an increased hardness relative to the friction surfaces. Such a mixture can be considered as a polydisperse system consisting of abrasive material particles, wear particles formed during friction and additionally introduced ultradisperse particles introduced as an additive.

Wear particles can play an important function when introducing an ultrafine additive. When they are located in the friction zone, the ultrafine additive is transported both on the surface of the abrasive particles and with the help of wear particles. During the friction process, in the case of additives, it is possible to stabilize the system state and bring it to an equilibrium state, which avoids a catastrophic increase in the rate of abrasive wear due to an avalanche-like increase in the number of wear particles.

3.2. Research of I40-Taunit-M systems

At the first stage of the study, the effect of the introduction of the additive "Taunit-M" was determined at OMI-40A. The introduction of the additive led to a decrease in the diameter of the wear spot at
concentrations from 0.5 up to 2.0 weight%. At the same time, the composition showed the greatest effect with 1.5 wt. % (figure 3)

![Figure 3. The wear spot area.](image)

At the same time, the introduction of an additive at all concentrations led to an increase in the friction moment (figure 4)

![Figure 4. The values of the friction torque during the test.](image)

The obtained photos of wear spots may indicate that when carbon nanotubes are introduced as a lubricant additive, their effect largely consists in the formation of a carbon film on the contacting surfaces. As you can see (figure 5), with an increase in the concentration of the additive, a visual increase in carbon is noticeable on the surface of the wear spot, which may indicate work in the process of friction of carbon films.
3.3. Research of I40-Taunit-M systems contaminated with abrasive material

At the second stage of the study an abrasive material Corundum was introduced into the lubricant 25А 0.063-0.125 (F180).

Tests have shown that adding of 0.5 wt. % abrasive agent leads to a sharp increase in the diameter of the wear spot (more than twice). While this, the introduction of "Taunit-M" led to a decrease in the abrasive effect of corundum particles.

The greatest effect from the introduction of nanoparticles was 23% in case of mass concentration of the additive 1.0 wt. % (figure6).

Figure 5. Structure of the wear spots: (a) I40; (b) I40 + 0.25 wt. % «Taunit-M»; (c) I40 + 0.5 wt. % «Taunit-M»; (d) I40 + 1.0 wt. % «Taunit-M»; (e) I40 + 2.0 wt. % «Taunit-M»; (f) I40 + 0.5 wt. % Corundum; (g) I40 + 0.5 wt. % Corundum + 1.0 wt. % «Taunit-M»; (h) I40 + 0.5 wt. % Corundum + 2.0 wt. % «Taunit-M».

Figure 6. Area of the wear spot when introducing abrasive material.
At the same time, when the abrasive material was introduced, the friction mode was unstable. In the range from 250 to 350 seconds after the start of the test, there was a sharp increase in the friction moment. In the case of a system with a lubricant contaminated with abrasive, an abrupt increase in the friction moment can be observed, which may indicate instability. Introduction of the additive at a concentration of 1.0 wt. % had no effect on this phenomenon, but an increase in the concentration to 2.0 wt. % resulted in stabilization of the (figure 7).

![Figure 7. Area of the wear spot when introducing abrasive material.](image)

The dependence of the area of the wear spot on the additives and abrasives introduced can be represented as a histogram (figure 6).

The temperature dependence was also analyzed during the experiment. Introduction of carbon nanotubes in concentrations of 0.25 and 0.5 wt. % resulted in a slight increase in temperature at the end of the test. The introduction of UNT Taunit-M at a concentration of 1.0 and 2.0 wt. % resulted in a slight decrease in system temperature.

In the case when the I40 lubricant was contaminated with abrasive corundum particles, the additional introduction of carbon nanotubes led to an increase in the system temperature (table 3).

| Lubrication material | Temperature variation, °C |
|----------------------|---------------------------|
| I40                  | 13.79                     |
| I40 + 0.25 wt. % «Taunit-M» | 14.21                    |
| I40 + 0.5 wt. % «Taunit-M» | 13.26                    |
| I40 + 1.0 wt. % «Taunit-M» | 11.06                    |
| I40 + 2.0 wt. % «Taunit-M» | 11.34                    |
| I40 + 0.5 wt. % Corundum 25A | 15.08                    |
| I40 + 0.5 wt. % Corundum 25A + 1.0 wt. % «Taunit-M» | 15.61                    |
| I40 + 0.5 wt. % Corundum 25A + 2.0 wt. % «Taunit-M» | 18.06                    |
4. Conclusion
As a result of tests, it was shown that the introduction of carbon nanostructures "Taunit-M" as an additive reduces wear both in the base oil and in the Oil with the addition of abrasive particles. Photos of the friction surface after testing may indicate that in the case of base oil, the reduction in wear is due to the formation of an additional layer of graphite between the contacting surfaces.

In the case of a composition with abrasive particles, there are practically no traces of carbon on the friction surface. In this case, we can consider the interaction of carbon nanotubes directly with abrasive particles. Abrasive wear can be reduced due to the "shielding" effect of nanoparticles, which, when they come into contact with corundum, reduce the cutting effect of particles on the surface of the ball.

It can be assumed that carbon nanotubes can shield the cutting action of abrasive particles by electrostatically interacting with them. Carbon nanotubes, having a sufficiently large stiffness and small size, are fixed to the abrasive particles, damping the impact of the abrasive particle on the friction surface, while passing directly to the surface itself. To sum up, two processes can occur: reduced cutting action of the abrasive and additional transfer of carbon nanoparticles to the friction surfaces.

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