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Interrelation of the volume temperature of modified oils and local temperatures in the friction contact zone under extreme operating conditions

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Abstract

A methodology has been developed that allows, using the temperature criterion, to determine the thermomechanical stability of oils and, thus, to analyze the modification of oils to improve the lubrication efficiency and wear resistance of friction pairs of conformal internal combustion engine units operating under extreme conditions. The correlation relationship between the temperature in the local frictional contact zone and the bulk temperature of the modified oil was determined with an increase in the maximum contact stress during the running-in period with a corresponding shift of the correlation linear dependences towards high temperatures. Under conditions of operation up to 15 cycles, increased thermomechanical stability of the modified oil was established in comparison with the standard oil, which confirms the optimal structural adaptability of the modified layers to extreme operating conditions.

Key words: conformal friction assembly, thermomechanical stability, wear resistance, oil modification, extreme operating conditions, temperature in the friction contact, oil temperature, thermal method.

Introduction

From the point of view of energy efficiency and national security, at strategic enterprises of the oil and gas, thermal power and aerospace complexes, in the production of high-speed transport, agricultural and military hybrid equipment, predicting the effectiveness of lubrication and wear resistance of the friction pairs, especially for friction units operating under extreme operating conditions, is a necessary direction to increase reliability and extend the service life in a wide range of changes in contact loads, speeds, temperatures, impacts, etc.

Extreme operating conditions for friction units will arise in case of insufficient lubrication (lubrication starvation), when the lubricant does not have time to regularly enter the contact zone due to several reasons: 1) non-stationary friction conditions in the "stop-and-go" mode; 2) loss of mechanical stability of the lubricant due to the manifestation of non-Newtonian properties at high shear rates under low-temperature start-up conditions; 3) insufficient structural adaptability of the modified layers under conditions of boundary lubrication at local temperatures in the friction contact zone.

For extreme conditions of operation of an internal combustion engine (ICE)'s the conformal friction assembly under sliding friction, an important aspect is the temperature factor, namely, it is important to compare the average local temperature in the friction contact zone and the critical local temperature, which will be determined by thermomechanical stability under conditions of plastic-deformed contact in the boundary lubrication mode, for example, in the zone of the upper dead center (UDC) along the piston stroke of an ICE.

The purpose of the work

To develop a methodology that will allow, by means of a correlation assessment between the volumetric and local temperatures in the friction contact zone, to determine the thermomechanical stability of modified and standard oils under all other operating conditions and, thus, to analyze the modification of oils according to the appropriate temperature criterion to improve the lubrication efficiency and wear resistance of the friction pairs of an ICE's the conformal friction assembly in extreme operating conditions.

Methodical support for determination of thermomechanical stability of the oils in an ICE's the conformal friction assembly under non-stationary friction conditions

The basic principle of choosing a tribological test scheme with consideration of the temperature factor under unsteady-state friction conditions is to maximize the approximation to the actual operating conditions of the studied tribological couplings. To do this, it was necessary to ensure that the nature of the movement of the samples, sliding values and speeds, as well as the materials of the friction pairs, which simulate the conditions of friction units in the "stop-end-go" mode, were consistent. When choosing a schematic diagram for studying the processes of friction and wear of moving joints in lubricants, it was necessary to take into account the qualitative picture obtained on the samples observed when the conditions of intensive wear of friction pairs of an ICE's the conformal friction assembly are realized, namely, when the compression ring - inner wall of the working cylinder contacts with full contact of the contact surfaces under conditions of pure sliding friction.

The studies were carried out on a modernized universal automated friction test bench (UAFTB) based on the SMC-2 friction machine (Fig. 1), which is based on the method of measuring the voltage in the normal glow discharge (NGD) mode [1], which is based on the theory of the occurrence of a glowing gas discharge in a lubricant (oil) associated with the formation of gas bubbles.

The chosen research scheme (see Fig. 1) has the following advantages:

- the possibility of changing the temperature in the range from minus 20^0C to 150^0C, which does not affect the value of the voltage drop;
- the voltage drop almost does not depend on the properties and composition of oils, since the discharge occurs in gas;
- moisture content and wear products, as well as the properties of the metal surfaces of friction pairs, do not affect the voltage value;
- the ability to measure separately the thickness of lubricating layers of different origin, which is ideal for mixed friction conditions.

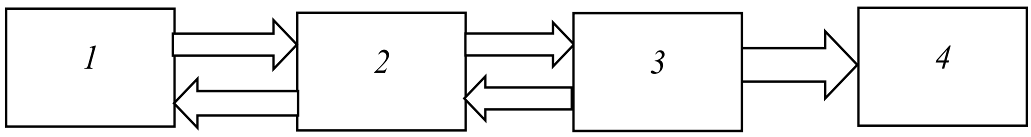


Fig. 1. Block diagram of the UAFTB: *1* - Friction machine SMC-2; *2 - 4*: Automated control unit with software (ACUS), which includes: 2 - Strain gauge unit; 3 - Analog-to-digital converter (ADC); 4 - PC software

According to the kinematic diagram, the SMC-2 friction machine (Fig. 2) is a single-contact unit consisting of a pad-roller sample mounting unit for clean sliding conditions in a non-stationary friction mode (Fig. 3).

Fig. 2. General view of the UAFTB

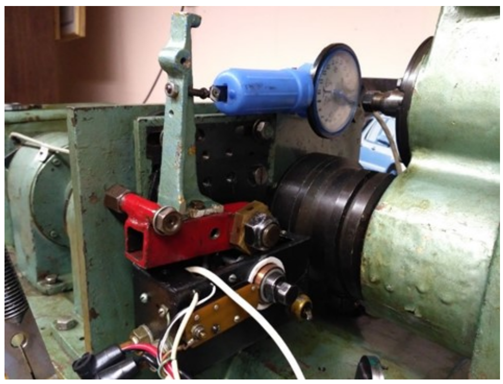


Fig. 3. Pad-roller tribopair at the SMC-2

For the exchange of parametric information between the primary transducer (strain gauge) and the PC (see Fig. 1), a programmable complex is used, which includes an analog-to-digital converter (ADC) "eZtrend V5" by Honeywell, designed to switch analog signals and convert them into digital code. The program implements the hardware launch of the ADC. The ADC request is executed before the converter is ready. For hardware startup of the ADC at different intervals, a timer is used, which is part of the universal programmable complex.

Measurement and control of the volumetric temperature is carried out using a digital thermostat TR-3 with built-in temperature sensors and a measuring range from minus 20°C to 150°C. Forced heating of the oil to the set temperature is carried out using a heating element - a heating element. Low temperature conditions are ensured by the circulation of carbon dioxide from the Dewar tank (see Fig. 2). To investigate the relationship between the volumetric temperature of the oil under study, measured by a thermocouple, and the local temperature in the local friction contact zone, we used the thermal imaging method of measuring the field of local temperatures using different modes of loading in the contact.

The thermal imaging method allows us to study the change in local temperatures of friction units in the friction contact zone and beyond using a modern portable thermal imager TESTO-875-2i (Fig. 4).

Fig. 4. General view of the portable thermal imager "TESTO-875-2i"

The technical characteristics of the portable thermal imager of this brand are as follows:
- detector 160 x 120 pixels, uncooled microbolometer;
- thermal sensitivity - 0.08 °C;
- spectral range 8...14 microns;
- 3.5' LCD display, 320 x 240 pixels;
- image viewing - infrared and real (digital camera);
- temperature measurement range (- 20 ... + 280 °C);
- measurement error - 2°C;
- minimum focal length - 0.4 m;
- 2GB memory card (approximately 1000 images);
- power supply from lithium batteries;
- operating ambient temperature - from (-15°C) to (+50°C);
- battery life - 4 hours;
- weight about 900 g.

Results of studying the thermomechanical stability of oils in the friction contact zone of an ICE's the conformal friction assembly

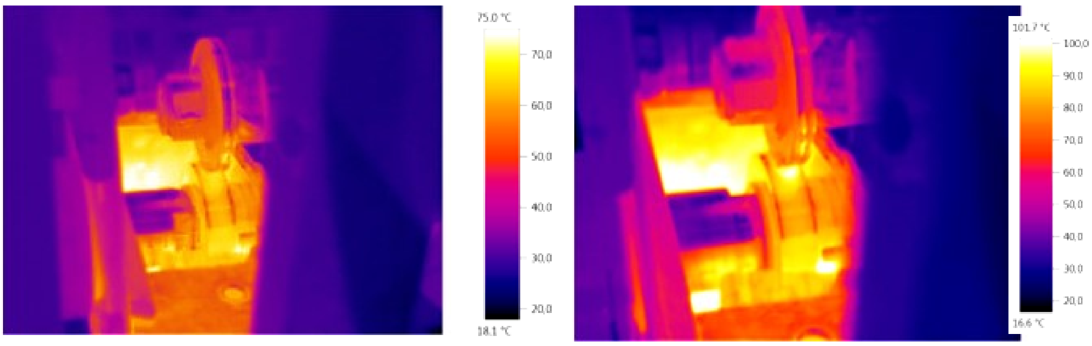
As the lubricant under study, we used a modified motor oil with the addition of a mixture of fullerenes with a concentration of the 2% according to the preliminary results obtained in [2, 3]. Temperature studies were conducted in 2 stages:

Stage 1 - thermal imaging measurement of the temperature fields of the local roller contact zone and the volumetric temperature for the modified oil under atmospheric conditions – $T = 291$ *K* at the maximum contact stress in the contact, $\sigma_{max} = 55$ *MPa.* The temperature regime of heating was as follows: *T = 303K; 313K; 318K; 338K; 348K; 353K; 363K* respectively.

Stage 2 - thermal imaging measurement of the temperature fields of the local contact zone of the roller and the volumetric temperature for the modified oil under atmospheric conditions – *T = 291K* at the maximum contact stress in the contact, $\sigma_{max} = 68$ *MPa*.

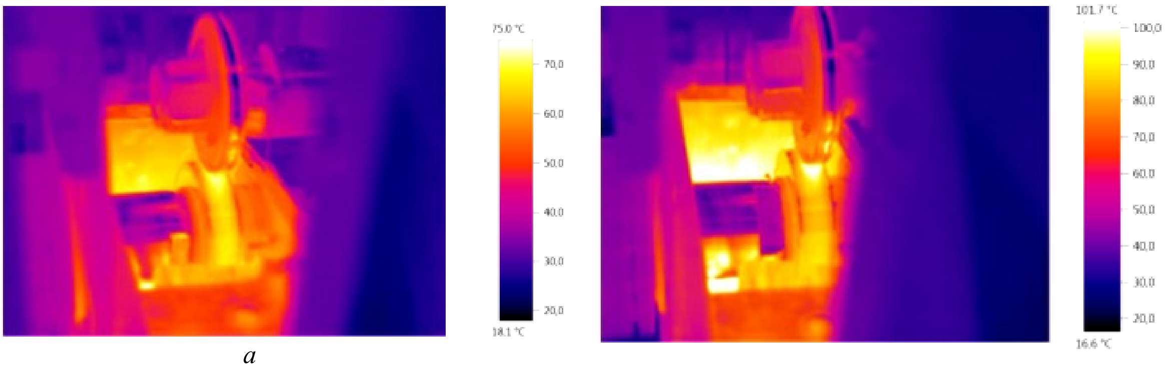
The temperature regime of heating was as follows: *T = 303K; 313K; 318K; 338K; 348K; 353K; 363K* respectively. The initial operating period was reproduced for different shaft rotation cycles: *5 cycles, 10 cycles,* and *15 cycles*, respectively.

The results of the thermal imaging tests are presented in the form of thermograms for the maximum contact stresses in the contact $\sigma_{max} = 55$ *MPa* (Fig. 5 *a, b*) and $\sigma_{max} = 68$ *MPa* (Fig. 6 *a, b*) at *T = 348K* and *T = 363K*, respectively.



a *b*

Fig. 5. Thermogram of the temperature fields of the contact zone: for the initial operating period at σ_{max} = 55 MPa during heating to T = 348K (a) and T = 363K (b), respectively



a

Fig. 6. Thermogram of the temperature fields of the contact zone: for the initial operating period at σ_{max} = 68 MPa during heating to T = 348K (a) and T = 363K (b), respectively

Below, we present the results of the studies in tabular form (Table 1) and graphical interpretation of the results (Fig. 7) at the maximum contact stress in the contact, $\sigma_{max} = 55\ MPa$ for the initial operating period.

According to the results in Fig. 7, a correlation was established between the temperature of the roller in the local friction contact zone and the volumetric temperature of the modified oil for the initial operating period at $\sigma_{max} = 55\ MPa$, which ranges from 6% to 34% as the temperature increases in the studied range. Moreover, the temperature of the roller increases linearly, reaching a maximum temperature of $T = 380K$ at the end of the operating time, at which the temperature difference between the oil and the roller is equal on average to $\Delta T = 25K$.

The following research results are presented in tabular form (Table 2) and in the form of a graphical interpretation of the results (Fig. 8) at the maximum contact stress in the contact $\sigma_{max} = 68\ MPa$ for the initial operating period.

Table 1

Results of correlation between the roller's local temperature and the modified oil's volumetric temperature at the maximum contact stress in the contact, $\sigma_{max} = 55\ MPa$

Object of research	№, cycles	Correlation between roller temperature and oil temperature, taken from the thermogram, ^{0}C						
		Oil heating temperature by thermocouple, ^{0}C						
		30	40	45	65	75	85	90
Oil	5	45.3	48.2	48.5	62	73.5	71.9	80.4
Oil	10	46.3	49	52.8	67.2	73.2	77	78.4
Oil	15	43.8	47.2	55.4	63.6	70.3	80.9	81.9
Roler	15	47.6	48	76.1	85	90.2	100	107

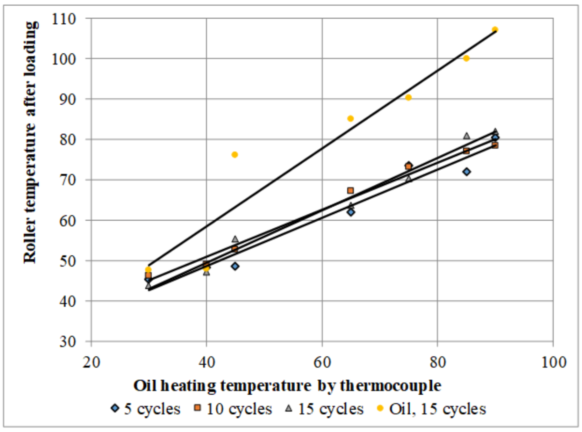


Fig. 7. The correlation between the local temperature of the roller in the contact zone and the volumetric temperature of the modified oil during the initial operating period at σ_{max} = 55 MPa

According to the results of Fig. 8, a correlation was established between the temperature of the roller in the local contact zone and the volumetric temperature of the modified oil for the initial operating period at $\sigma_{max} = 68$

MPa, which ranges from 4% to 58% as the temperature increases in the studied range. Moreover, the temperature of the roller increases linearly, reaching a maximum temperature of $T = 382.4K$ at the end of the operating time, at which the temperature difference between the oil and the roller is equal on average to $\Delta T = 40K$.

Thus, the results of the correlation between the local temperature of the roller in the local contact zone and the volumetric temperature of the modified oil, for the initial operating period with an increase in the maximum contact stress σ_{max} from *55 MPa* to *68 MPa*, extends the spread of the correlation linear dependences towards high temperatures by an average of $\Delta T = 15K$, which determines the importance of taking into account the increase in the local temperature of the roller in the local friction contact zone relative to the oil volume temperature with increasing load (maximum contact stress).

In order to determine the thermomechanical stability, it is necessary to know the average temperature in the local contact zone, taking into account the correlation between the volume temperature of the modified oil and the local temperature in the friction contact zone, where the temperature fields (changes in the special temperature point) are determined by the thermal imaging method for the roller-pad friction pair ("roller" - made of Steel 40H, "pad" - made of bronze BrOCS 4-4-17) during the period from startup to *15* cycles in the non-stationary sliding friction mode at different warm-up temperatures: $T = 298K; 303K; 313K; 338K; 348K$, respectively.

By the thermal imaging method of research, the fields of local temperatures in the friction contact zone of the roller (changes in the special point of the corresponding temperature) were determined in the form of thermograms (Fig. 9, where it is shown for $T = 298\ K$) and changes in local temperatures in the friction contact zone of the roller were determined (Fig. 10, *a-d*) relative to the volumetric temperature of the studied modified oil measured by a thermocouple, taking into account the correlation performed during the period from startup to *15* cycles in the unsteady-state mode of sliding friction at different heating temperatures.

Table 2

Results of correlation between the roller's local temperature and the modified oil's volumetric temperature at the maximum contact stress in the contact, $\sigma_{max} = 68$ MPa

Object of research	№. cycles	Correlation between roller temperature and oil temperature. taken from the thermogram. ^{0}C						
		Oil heating temperature by thermocouple. ^{0}C						
		30	40	45	65	75	85	90
Oil	5	38.2	45.9	47.4	56.1	55.9	68.5	69.1
Oil	10	35.3	43.5	48.1	50.5	64.2	67.1	69.6
Oil	15	35.3	42.4	49.9	59.4	55.9	71.5	68.6
Roler	15	35.3	44.5	76.1	83.7	89.3	99.3	109.4

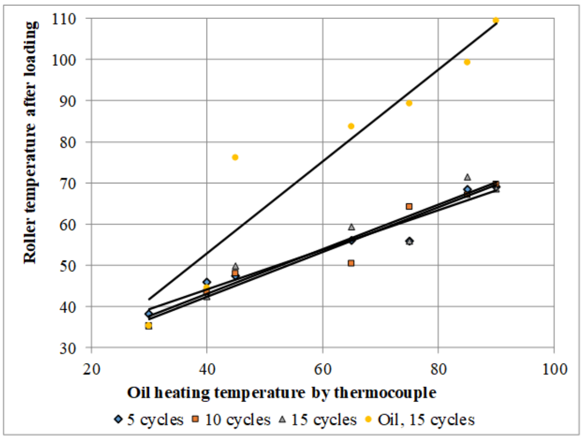


Fig. 8. The correlation between the local temperature of the roller in the contact zone and the volumetric temperature of the modified oil during the initial operating period at σ_{max} = 68 MPa

Based on the results of the fields of local temperatures (thermograms) of the roller surface (see Fig. 10 *a-d*), special points of local temperature in the friction contact zone were determined, taking into account the preliminary correlation between the local temperature of the roller surface and the volumetric temperature measured by the thermocouple for the studied oils: modified oil and standard oil selected for comparison during the operating period.

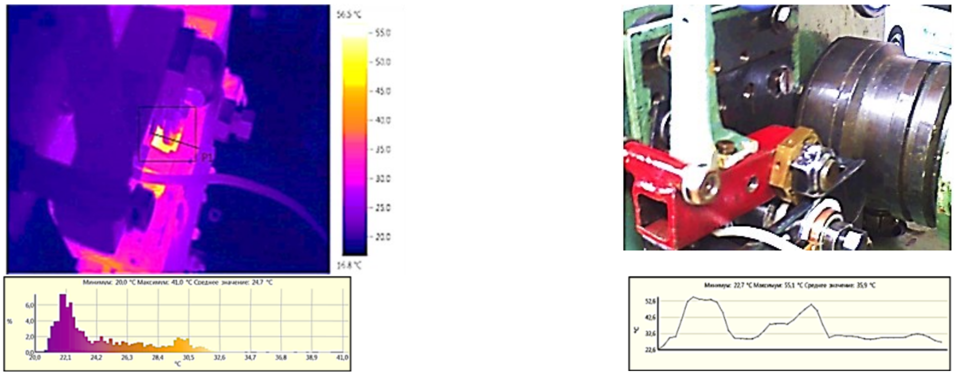


Fig. 9. Thermogram of a special point of local temperature in the friction contact zone of the roller at T = 298K during the initial operating period

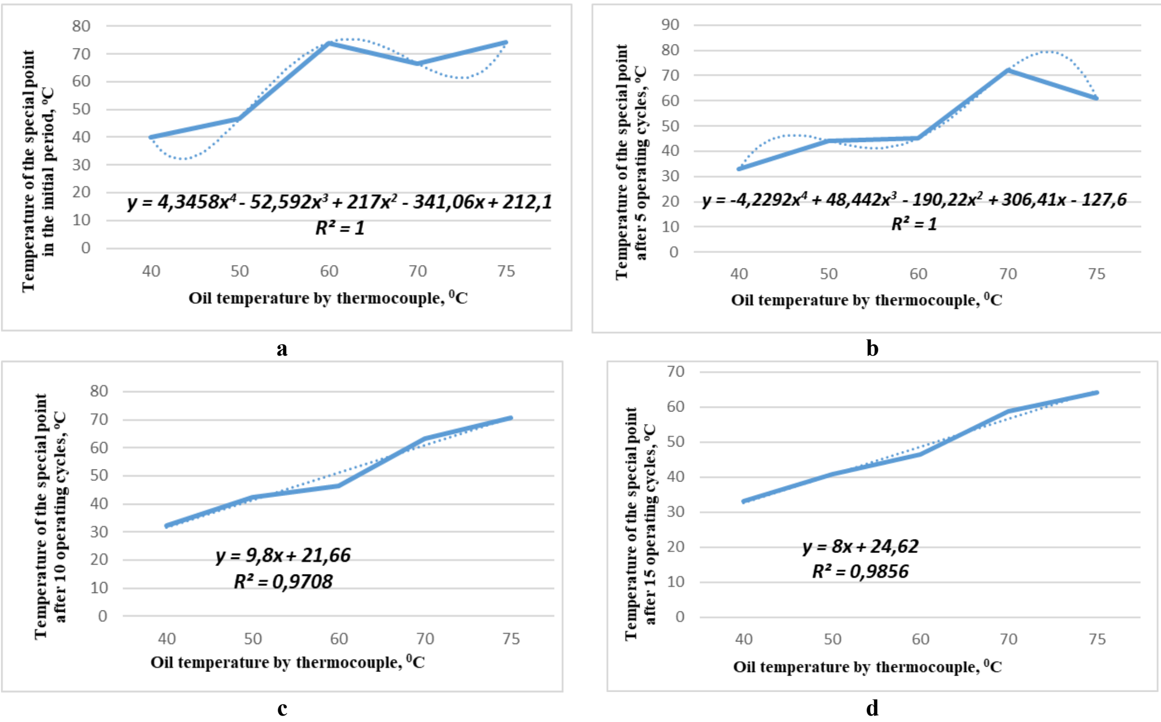


Fig. 10.- Change of the local temperature feature point regarding the previous correlation: in the initial operating period (a), after 5 (b), -10 (c), -15 (d) operating cycles

According to the equations (see Fig. 10 *a - d*), it was determined that under the conditions of operating time up to *15* cycles, the condition for the temperature criterion is met: $T_{critical} < T_{average}$ for both oils, but for the modified oil, an increased thermomechanical stability was established, on average by $\Delta T = 23K$, which confirms the better structural adaptability of the modified layers of the corresponding modified oil to extreme operating conditions.

Conclusions

The correlation between the temperature in the local friction contact zone and the volumetric temperature of the modified oil was determined when the maximum contact stress was increased to *68 MPa* during the running-in period with a corresponding shift of the correlation linear dependencies towards high temperatures by $\Delta T = 15K$. Under the conditions of operating up to *15* cycles, the thermomechanical stability of the modified oil was found to be increased compared to the standard oil, on average by $\Delta T = 23K$, which confirms the optimal structural adaptability of the modified layers to extreme operating conditions.

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Міланенко О., Савчук А., Кущ О., Бобро А., Вансовський О. Взаємозв'язок об'ємної температури модифікованих олив і локальних температур у зоні контакту тертя в екстремальних умовах експлуатації

Розроблено методику, яка дозволяє за допомогою температурного критерію, визначати термомеханічну стійкість олив і, таким чином, аналізувати модифікування олив щодо підвищення ефективності мащення і зносостійкості пар тертя конформних вузлів ДВЗ, які працюють в екстремальних умовах роботи.

Визначено кореляційний взаємозв’язок між температурою в локальній зоні фрикційного контакту і об’ємною температурою модифікованої оливи при збільшенні максимального контактного напруження до *68 МПа* в період припрацювання з відповідним рознесенням кореляційних лінійних залежностей в бік високих температур на $\Delta T = 15K$. В умовах напрацювання до *15* циклів, встановлена збільшена термомеханічна стійкість модифікованої оливи в порівнянні зі штатною оливою, в середньому на $\Delta T = 23K$, що підтверджує оптимальну структурну пристосовуваність модифікованих шарів до екстремальних умов роботи.

Ключові слова: конформні вузли , термомеханічна стійкість, ефективність мащення, зносостійкість пар тертя, модифікування олив, структурна пристосовуваність,температура контакту, температура оливи, тепловізійний метод.