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Assessment of Antifriction Characteristics of Friction Pairs with Solid-Lubricating Coatings under Various Operating Conditions

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Abstract—This work deals with the development of a method for assessing the antifriction characteristics of friction pairs with solid-lubricating coatings for an arbitrary combination of the load and velocity parameters of friction using the dependences of the friction temperature on these load and velocity parameters of the operation of the pairs and the correlation dependences of the coefficient of friction on the friction temperature. Based on the experimental data and the information reported in the literature, the dependences for the friction pairs of various compositions are obtained for normal atmospheric and vacuum conditions.

Keywords: antifriction characteristics, solid-lubricating coatings

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INTRODUCTION

Solid-lubricating coatings (SLCs), including VNII NP, VAP, and others, are widely used to lubricate self-contained friction units that operate under extreme conditions of a normal atmosphere and a vacuum [1–3]. At present, it is difficult to assess the antifriction characteristics of these friction units for an arbitrary combination of the contact pressure (P) and the velocity of sliding (V) because of the lack of relevant methods for calculating these characteristics; the information presented in the literature contains only single-factor dependences of the coefficient of friction on the load, the velocity of sliding, etc.

The aim of this work was to develop a calculation-experimental method for assessing the coefficient of friction of units with SLCs of various compositions for an arbitrary combination of the operating parameters, such as the contact pressure and the velocity of sliding.

EXPERIMENTAL

The joint effect of the load and velocity parameters on the coefficient of friction of the pairs with SLCs at normal and elevated temperatures was studied using an SMT friction machine and a modernized setup for complex tribotests at elevated temperatures, which was based on a roller-friction machine and implemented the infinitely variable control of the friction parameters [4]. The investigation of the performance of the friction pairs with SLCs and other lubricants under vacuum conditions was carried out using a workbench for studying friction and wear in vacuum the design of which was patented (USSR Inventor's Certificate no. 926573). The tests that involved the end-friction contact were performed using a washer–disk workbench. The specimens were made of C60 (HV_{30} 300, 500, and 700–800) and ShKh15 steels. We tested SLCs of the All-Russian Scientific Research Institute for Petroleum Processing (VNII NP) and Molikote 7409 (Germany).

Results of the study showed that the antifriction characteristics of the SLCs are closely related to the thermal state of the surface of the friction contact [4]. It is known that the friction temperature T_{fr} depends on the load and velocity parameters of the operation of friction units as follows: $T_{fr} = f(P, V)$. Therefore, if dependences $f_{fr} = f(T_{fr})$ for pairs with various SLCs are known, the corresponding antifriction characteristics of these pairs can be assessed.

In accordance with the temperature method described in work [5], the total test temperature is determined as the sum of the bulk temperature T_b and the friction temperature T_{fr}, which is either calculated theoretically or found experimentally. We developed a method for assessing the antifriction characteristics of friction pairs with SLCs of various compositions; this method is implemented using the following algorithm:

(1) the assessment of the contact pressure P and the velocity of sliding V for a real friction unit;

(2) the calculation of the friction temperature T_{fr} using the obtained dependences of this temperature on the contact pressure P and the velocity of sliding V (if the friction unit operates at the elevated temperature T_b, this temperature is added to T_{fr});

Table 1. Dependences $T_{fr} = f(P, V)$ for different friction-contact arrangements and ranges of variation in factors

SLC type	Friction contact arrangement	Ranges of variation		Dependences $T_{fr} = f(P, V)$
		N, N (P, MPa)	V, m/s	
VNII NP 212	Rolle (modernized RP friction machine)	236–1337 (23.1–133.7)	0.096–1.224	$T_{fr} = 36.49 + 132.23V + 0.535P + 0.234PV - 47.94V^2 - 2.094 \times 10^{-3}P^2$
VNII NP 212	Roller (SMT friction machine)	210–1790 (12.2–103.5)	1.472–3.728	$T_{fr} = 119.35 + 10.26V + 0.065P + 0.335PV$
Molykote 7409	End (washer–disk workbench)	755–9045 (5.6–67.2)	0.11–0.25	$T_{fr} = 67.27 - 98.96V + 0.464P + 6.42PV - 0.011P^2$

V is measured in m/s, P is measured in MPa, and T_{fr} is measured in °C.

(3) the calculation of the coefficient of friction f_{fr} using the correlation dependences of this coefficient on the friction temperature T_{fr}.

RESULTS AND DISCUSSION

Assessment of Antifriction Characteristics of Friction Pairs with SLCs under Normal Atmospheric Conditions

Because of the need to assess the antifriction characteristics of the friction pairs with the SLCs using various friction contact arrangements and in order to widen the ranges of the load and the velocity of sliding to obtain dependences $T_{fr} = f(P, V)$, we carried out experiments using second-order central composite rotatable uniform design and obtained the mathematical models of the dependence $T_{fr} = f(P, V)$ for different friction-contact arrangements and ranges of variations in the factors (Table 1) [4]. These dependences are located on a single surface, which confirms their universality.

At the next stage, we determined the dependences $f_{fr} = f(T_{fr})$ for different types of SLCs in order to implement the third stage of the algorithm. The correlation dependence $f_{fr} = f(T_{fr})$ for the SLC VNII NP 212 was determined as a result of processing the experimental data obtained under normal atmospheric conditions and at an elevated temperature using the setup for complex tribotests at elevated temperatures as follows [4] (Fig. 1):

$$f_{fr} = 0.01197 + 8.881T_{fr}^{-1}. \quad (1)$$

An analysis of our experimental data presented in Fig. 1 has shown that, even at the total test temperature (which is the sum of the friction temperature T_{fr} and the temperature of heating T_b) of over 320°C, the friction pair operates for 1–1.5 h and exhibits a low coefficient of friction ($f_{fr} = 0.04$). In experiments carried out with the same SLC VNII NP 212 using a KT-2 four-ball friction machine at a temperature of over 220°C, a gradual increase in f_{fr} is observed. Therefore, we checked the correctness of the values of the coefficient of friction for the temperature range of 70°C (the lower limit in Fig. 1) to $T_{fr} = 220$°C.

The results presented in Table 2 show that the deviation of our data from the results reported in work [5] is 16–30%, which is considered to be satisfactory for tribotests. The coefficient of friction of the pairs with the SLC VNII NP 213 was calculated using the above-described method and the dependence proposed by Prof. Matveevskii [5].

The approximation of the dependence $f_{fr} = f(T_{fr})$ for the SLC VNII NP 213, which was carried out using the parabolic interpolation procedure [6], has yielded the following dependence:

$$f_{fr} = 0.1223 - 0.00047T_{fr} + 6.29 \times 10^{-7}T_{fr}^2. \quad (2)$$

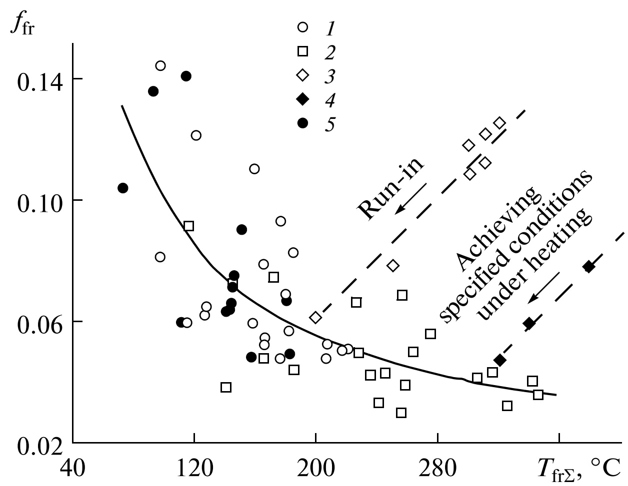

Fig. 1. Results of experimental study of thermal-friction state of pair with SLC VNII NP 212 under various conditions: (*1*) steady friction (before heating of friction pair); (*2*) friction under heating; (*3*, *4*) run-in before heating and achieving specified conditions under heating, respectively; and (*5*) steady friction (according to data obtained in experiment without heating carried out to determine dependence $f_{fr} = f(P, V)$).

Table 2. Check of validity of correlation dependence (1) of coefficient of friction on test temperature for pair with SLC VNII NP 212

Friction pair type	Literature data		Data calculated using formula (1)	Deviation, %
	T_{fr}, °C	f_{fr}	f_{fr}	
Four-ball arrangement, SLC VNII NP 212 [5], KT-2 friction machine	70	0.12	0.139	13.7
	120	0.11	0.086	21.8
	170	0.08	0.064	19.7
	220	0.075	0.052	30.2

High-temperature SLCs TsVSP-3c and VNII NP 229, which contain sodium silicate as the binder, are widely used in the design practice. In connection with this, at the next stage, we carried out an analysis of the experimental data for these SLCs obtained in work [7].

The approximation of the dependences $f_{fr} = f(T_{fr})$ for the SLCs under consideration has yielded the following dependences:

—for the SLC TsVSP-3c,

$$f_{fr} = 0.0896 - 1.47 \times 10^{-4} T_{fr} + 3.464 \times 10^{-7} T_{fr}^2 \text{ and,} \quad (3)$$

—for the SLC VNII NP 229,

$$f_{fr} = 0.0821 - 1.4 \times 10^{-4} T_{fr} + 2.72 \times 10^{-7} T_{fr}^2, \quad (4)$$

where T_{fr} is measured in degrees Celsius.

Table 3. Conditions and results of experiment on studying effect of operating parameters on performance of friction pairs with SLC Molykote 7409 carried out using second-order central rotatable design (steel C60, $HV_{30\,HT}/HV_{30\,LT} = 770/780$)

Experiment no.	Levels of factors on natural scale		Optimization parameters	
	V, m/s	P, MPa	T_{fr}, °C	f_{fr}
1	0.23	58.2	119	0.062
2	0.13	58.2	97	0.066
3	0.23	14.6	67	0.092
4	0.13	14.6	73	0.100
5	0.25	36.4	104	0.075
6	0.11	36.4	77	0.088
7	0.18	67.2	103	0.052
8	0.18	5.6	59	0.135
9	0.18	36.4	93	0.076

Molykote 7409 is considered to be one of the best foreign-made SLCs. These coating was tested using the end contact arrangement, which was implemented in the washer–disk workbench [4]. The experiment that involved the simultaneous recording of the coefficient of friction and the friction temperature has yielded the data presented in Table 3.

Using the statistical processing of the data from Table 3, the following correlation dependence for the friction pair with the SLC Molykote 7409 was obtained:

$$f_{fr} = f(T_{fr}) = 9.5469 T_{fr}^{-1.076}. \quad (5)$$

The graphic interpretation of the obtained correlation dependences $f_{fr} = f(T_{fr})$ for the SLCs of various compositions is presented in Fig. 2.

An analysis of the dependences presented in Fig. 2 shows that, under the normal atmospheric conditions in the temperature range of up to 350–400°C, the friction pairs with Molykote 7409, VNII NP 213, and VNII NP 212 SLCs exhibit the best antifriction characteristics.

Assessment of Antifriction Characteristics of Friction Pairs with SLCs under Vacuum Conditions

Vacuum conditions are among the most important extreme conditions of the operation of friction units with SLCs. In connection with this, we solved the problem of determining the required correlation dependences for friction pairs with SLCs of various compositions under these conditions in order to implement the above-proposed algorithm.

The basic performance characteristics of friction units with SLCs were investigated using the workbench for studying friction and wear in vacuum, which was based on a roller friction machine and implemented the infinitely variable control of the load and velocity parameters of friction, as well as the continuous recording of the coefficient of friction f_{fr} and the friction temperature T_{fr} [4, USSR Inventor's Certificate no. 926573]. The experiments were carried out using second-order central

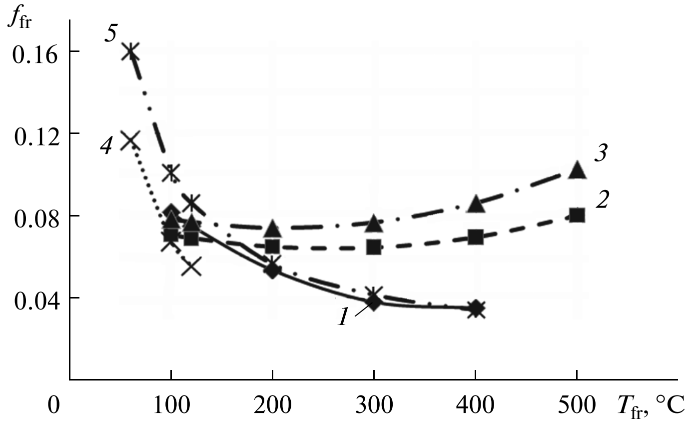

Fig. 2. Plots of correlation dependences $f_{fr} = f(T_{fr})$, which approximate experimental data for various SLCs: (*1*) VNII NP 213, (*2*) VNII NP 229, (*3*) TsVSP-3C, (*4*) Molykote 7409, and (*5*) VNII NP 212.

composite rotatable uniform design. The ranges of variations in the factors were as follows: V = 0.087–0.504 m/s, N [×9.8] = 130.5–60.0 N, and P = 61–121 MPa.

The study of the effect of the load and velocity factors on the friction temperature of the pairs with SLCs in a vacuum has yielded the following mathematical model expressed in the natural values of the factors:

$$T_{fr} = 3.31 + 291.64V + 0.643P_c - 282.19V^2. \quad (6)$$

As a result of carrying out the planned experiment under the vacuum conditions, which involved the simultaneous recording of the coefficient of friction and the friction temperature, the data presented in Table 4 were obtained.

Statistical processing of the data from Table 4 has yielded the following correlation dependence for the friction pair with the SLC VNII NP 212, which operates under vacuum conditions:

$$f_{fr} = 1.64T_{fr}^{-0.7155}. \quad (7)$$

The graphic interpretation of dependence (7) is presented in Fig. 3 compared with the similar characteristic obtained for normal atmospheric conditions.

The check of the validity of the method for assessing the antifriction characteristics of the pairs with the SLCs using the dependences $T_{fr} = f(P, V)$ and $f_{fr} = f(T_{fr})$ for the pair with the VNII NP 212 SLC, which operates in a vacuum (Fig. 3), has shown satisfactory results; the deviation is 15.4%, despite that the values of $Ð$ and V are outside the specified variation limits of the factors (Table 5).

An analysis of the literature data has shown that the required correlation dependences $f_{fr} = f(T_{fr})$ for the friction pairs with various SLCs for the vacuum conditions can be obtained using the experimental data presented in works [9, 10].

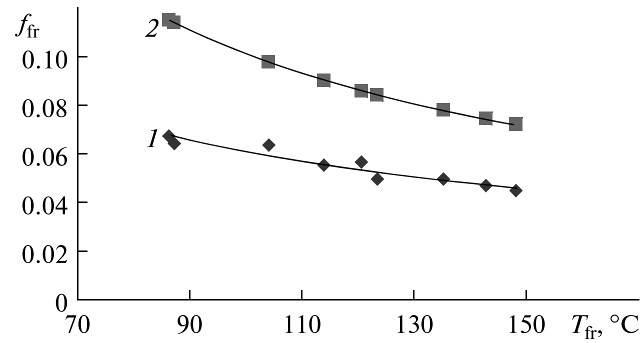

Fig. 3. Correlation dependences $f_{fr} = f(T_{fr})$ for friction pair with VNII NP 212 SLC obtained for various conditions: (*1*) vacuum and (*2*) normal atmosphere.

The experimental results were approximated using the parabolic interpolation procedure [6].

The approximation of the dependences $f_{fr} = f(T_{fr})$ for the SLCs under study and for the vacuum conditions has yielded the following dependences:

(1) for the SLC based on MoS_2 and the organosilicon binder K-55,

$$f_{fr} = 0.0905 - 3.46 \times 10^{-4}T_{fr} + 5.86 \times 10^{-7}T_{fr}^2; \quad (8)$$

Table 4. Conditions and results of experiment on studying effect of operating parameters on performance of friction pairs with SLC VNII NP 212 carried out under vacuum conditions using second-order central rotatable design

Experiment no.	Levels of factors on natural scale		Optimization parameters	
	V, m/s	$N \times 9.8$, N	T_{fr}, °C	f_{fr}
1	0.147	70.25	84	0.074
2	0.443	70.25	111	0.055
3	0.147	120.25	116	0.056
4	0.443	120.25	144	0.047
5	0.087	95.25	83	0.066
6	0.504	95.25	141	0.050
7	0.295	60.00	102	0.061
8	0.295	130.50	134	0.046
9	0.295	95.25	129	0.050
10	0.295	95.25	117	0.045
11	0.295	95.25	132	0.053
12	0.295	95.25	116	0.049
13	0.295	95.25	121	0.050

Table 5. Check of validity of method for assessing coefficient of friction for friction pair with SLC VNII NP 212 under vacuum conditions [8]

Friction pair type	Literature data		Calculation			Deviation of f_{fr}, %
	P, MPa	V, m/s	f_{fr}	T_{fr}, °C	f_{fr}	
Block-on-ring arrangement, $p = 10^{-3}$–10^{-4} Pa, SLC VNII NP 212 [8] for space applications	9.8 (outside range of variation)	0.008 (outside range of variation)	0.13	11.93	0.11	15.4

(2) for the SLC based on graphite and the organosilicon binder K-55,

$$f_{fr} = 0.1521 - 5.23 \times 10^{-4} T_{fr} + 5.6 \times 10^{-7} T_{fr}^2; \quad (9)$$

(3) for the SLC based on graphite and the binder Na_2SiO_3,

$$f_{fr} = 0.1167 - 4 \times 10^{-4} T_{fr} + 4.23 \times 10^{-7} T_{fr}^2, \quad (10)$$

where T_{fr} is measured in degrees Celsius.

The graphic interpretation of the correlation dependences $f_{fr} = f(T_{fr})$ for friction pairs of the SLCs of various compositions obtained for vacuum conditions is presented in Fig. 4.

An analysis of the dependences presented in Fig. 4 shows that the VNII NP 212 SLC, which operates under vacuum conditions at temperatures of 83–144°C, has one of the lowest coefficients of friction. At temperatures of up to 700°C, pairs with SLCs containing graphite, as well as the sodium silicate and organosilicon resin binders, exhibit the best antifriction characteristics.

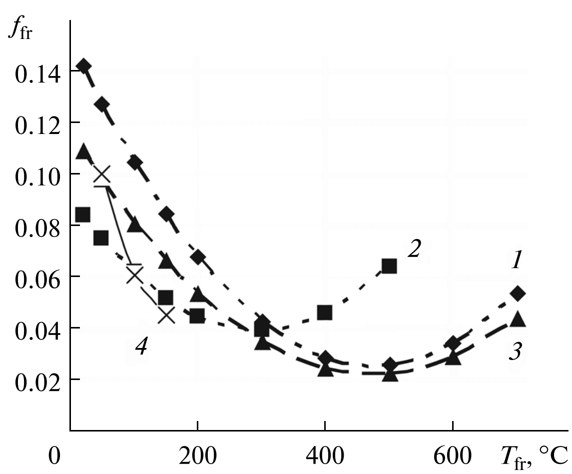

Fig. 4. Plots of correlation dependences $f_{fr} = f(T_{fr})$, which approximate experimental data for various SLCs under vacuum conditions: (*1*) graphite + organosilicon resin K–55; (*2*) MoS_2 + organosilicon resin K-55; (*3*) graphite + Na_2SiO_3; and (*4*) SLC VNII NP 212.

CONCLUSIONS

The results obtained have allowed us to draw the following conclusions:

(1) The method for assessing the antifriction characteristics of the friction pairs with the SLCs is developed, which is based on the use of the universal dependences of the friction temperature on the load and velocity parameters of the operation of the pairs $T_{fr} = f(P, V)$ and the correlation dependence of the coefficient of friction on the friction temperature $f_{fr} = f(T_{fr})$. The use of this method makes it possible to assess the antifriction characteristics of the friction pairs with the SLCs of various compositions for an arbitrary combination of the load and velocity parameters of friction units of real mechanisms, which operate under conditions of normal atmosphere and vacuum.

(2) In order to implement the proposed method, the experimental data were processed, which yielded the universal dependences $T_{fr} = f(P, V)$ for friction pairs with SLCs of various compositions and various friction contact arrangements, as well as the wide ranges of the load and velocity parameters, under conditions of normal atmosphere and vacuum.

(3) The correlation dependences $f_{fr} = f(T_{fr})$ are calculated, which make it possible to implement the proposed method under the following conditions:

—normal atmospheric conditions for friction pairs with VNII NP 212, VNII NP 213, TsVSP-3c, VNII NP 229, and Molykote 7409 SLCs;

—vacuum conditions for the friction pairs with VNII NP 212 SLC, as well as the SLCs based on MoS_2 and the organosilicon binder K-55, on graphite and organosilicon binder K-55, and on graphite and Na_2SiO_3 binder.

(4) Normal atmospheric conditions in the temperature range of up to 350–400°C the friction pairs with the SLCs Molykote 7409, VNII NP 213, and VNII NP 212 exhibit the best antifriction characteristics.

(5) Under vacuum conditions, at temperatures of 83–144°C, the pair with the VNII NP 212 SLC has one of the lowest coefficients of friction. At temperatures of up to 700°C, pairs with SLCs containing graphite, as well as sodium silicate or organosilicon resin binders exhibit the best antifriction characteristics.

NOTATION

P—contact pressure; *V*—velocity of sliding; f_{fr}—coefficient of friction; and T_{fr}—friction temperature.

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