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Tribological Properties of a Semi-Liquid Lubricant with Surfactant Additives

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Abstract—The properties of a semi-liquid lubricant (Lb) with additives were tested using a KT-2 oil testing machine; its stability and influence on the 'wheel flange—rail' friction pair was assessed. The analysis is based on laboratory wear tests of locomotive wheel flanges. Investigation of lubricants with additives showed their low colloidal stability, the highest oil release being observed with the addition of sulfo compounds and phospho additives. The thermal stability of lubricants with additives shows that at approximately 220°C the lubricants melt completely and turn into a liquid state. After conducting tribological tests on a KT-2 oil testing machine of a lubricant with a hydroquinone additive, white crystals formed on the surface of the facility. The dependence of the friction coefficient on the test temperature of the studied lubricant with additives was obtained. X-ray fluorescence analysis of the locomotive wheel flange surface showed a change in the concentration of chromium and manganese in the surface layer of the sample before and after bench tests, which may indicate the formation of a stable transfer layer providing good tribological properties. Empirical coefficients were obtained to determine the wear rate of the locomotive wheel flange for the studied additives.

Keywords: friction, wear, locomotive wheel flange, additives, lubricant, diffusion-active hydrogen

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INTRODUCTION

Hydrogen wear of locomotive wheel flanges is an important issue for railway transport. Equipment is exposed to active influence of hydrogen in spring and fall when humidity is high and in the northern regions of Russia. The theory of hydrogen wear involves mechanical and physicochemical mechanisms of destruction of the surface layer. Protection against hydrogen wear consists primarily in eliminating possible sources of hydrogen from the friction contact. It is generally accepted that hydrogen is generated from lubricants, however, the mechanism of hydrogen formation and the differences in the generation of hydrogen radicals in each lubricant are not clear. Available data indicate the following mechanisms of hydrogen formation from the lubricant [1–3]:

(1) Decomposition of the lubricant through a catalytic reaction with a juvenile metal surface.

(2) Breaking of molecular chains in the lubricant due to shear along the sliding surface.

(3) Thermal decomposition of the lubricant due to the release of heat during shear.

Hydrogen wear in the friction zone is a multi-stage sequential process. Depending on the mechanism of action of hydrogen, various methods of protection are used: covering active surface areas with a layer of neutral molecules, introducing copper oxide into composite materials, and addition of hydrogen penetration inhibitors. The use of lubricants with low hydrogenation also eliminates the formation of hydrogen. It is of importance to select a composition for railway transport that would reduce the amount of hydrogen generated and the coefficient of friction in the wheel flange—rail pair. During the operation of machine and vehicle parts, intensive release of diffusion-active hydrogen from the environment and the lubricant is observed; at low temperatures hydrogen concentrates in the friction zone of contacting surfaces, which leads to intense embrittlement and destruction of materials. Hydrogen, which is released from hydrocarbon lubricants when the temperature in the friction zone increases, initiates the destruction of polymers in the mixture with the formation of products, the dehydrogenation of which is accompanied by the release of hydrogen. Microscopic damages of the metal are acceptors of the produced hydrogen ions.

The semi-liquid lubricant employed to lubricate the wheel flanges of TEM type locomotives is used in the temperature range from –30 to +110°C; it features good adhesive properties, which enables its easy application to the vertical surface of the wheel flange, thus ensuring lubrication of the wheel—rail friction pair.

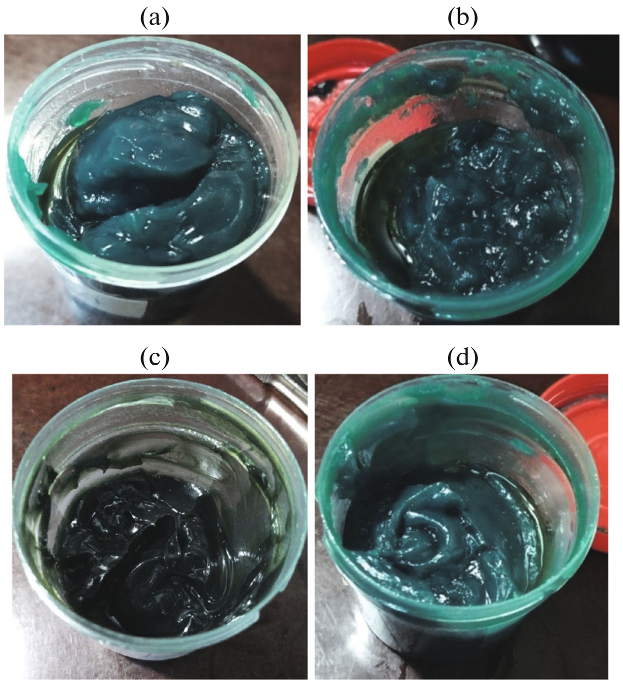


Fig. 1. Samples of semi-fluid lubricant: (a) without additives; (b) hosphor additive; (c) hydroquinone additive; (d) sulfo additive.

The lubricant is highly water resistant, preventing it from being washed away by precipitation.

The additives to be examined were chosen based on three parameters: compound class, corrosive properties towards metal, and surface wettability. The last two parameters are prerequisites in choosing an additive.

Objective—To determine an additive for a semiliquid lubricant that can enhance its anti-friction properties and reduce the release of diffusion-active hydrogen.

MATERIALS AND METHODS

The following additives were examined: organosulfonate additive, organophosphorus additive, and hydroquinone derivative additive, all of extra pure grade. Experimental studies included the production of a lubricant containing various additives in a ratio from 1 to 100 g of lubricant containing the sulfo group, $-SO_3R$, hydroquinone, $C_6H_4(OH)_2$, and phosphate groups. The selected additive-to-lubricant ratio is substantiated based on previously conducted studies, which found that as concentration of the additive in the lubricant increases, the antifriction properties of the lubricant do not change with respect to the selected ratio.

A ready-to-use thickener was used in production. If a ready-to-use thickener is used, it should be actively mechanically dispersed in oil in the process of heating. The process of adding the thickener was accompanied by constant stirring for 40 min and maintaining the production temperature. During the reaction, the fat is saponified to form soap and glycerin, while excess water evaporates. The stage of mixing the reagents is followed by cooling of the mixture, during which the structure of the lubricant is formed. Cooling was carried out in a special scraper refrigerator. Also, at the end of the procedure, selected additives were added to the lubricant, after which the mixture was subjected to mechanical processing using a three-roll paint grinder to ensure its homogenization and complete the formation of the material structure.

The tribological properties of the lubricant were determined using a KT-2 oil testing machine. Before the study, all parts of the oil testing machine were treated with solvent to remove lubricant and air dried. The temperature of the friction unit increased stepwise at a rate of ~4°C per min. The friction coefficient was assessed for 60 s every 10°C. The axial load on the friction unit was 108.4 N. To determine the wear rate of pure lubricant and additives introduced into it, a series of measurements were carried out for each sample. After each new measurement of a lubricant with an additive, parts were processed using KT-2. Table 1 displays the appearance of the lubricant with the studied additives during testing and variation of the temperature regime.

Products of wear in the lubricant were determined by X-ray fluorescence analysis (XRF). Wear of the flange friction surfaces was tested using a setup and the methodology presented in [4, 5]. A P65 rail was used as the analyzed sample; St2sp steel, which is employed as a wheel material on TEM-type diesel locomotives, was used as a counter sample. The studies included pre-treatment of rail and counterbody samples and preparation of lubricant and additives for it. Samples were cut from the rail and the wheel using a PM5GM machine so that the surfaces under study remained unchanged.

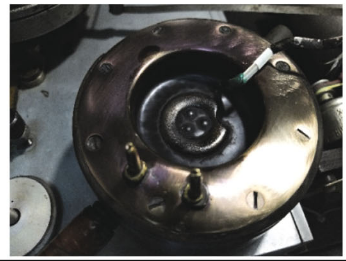
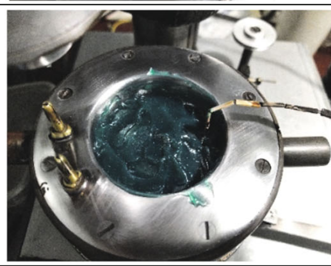
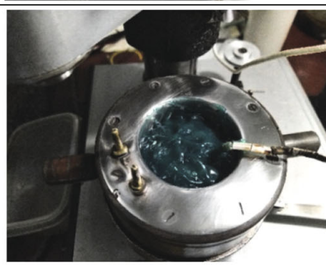
RESULTS AND DISCUSSION

The results of tests using the KT-2 machine are summarized in Table 2.

All lubricants release oil during storage, which indicates low colloidal stability of the lubricants (Fig. 1). The greatest oil release was observed for lubricants with sulfo compound and phospho additives (Figs. 1b, 1d).

Lubricants begin to noticeably melt at approximately 190–200°C; at approximately 220°C, lubricants melt completely and turn into a liquid state. After a lubricant with a hydroquinone additive was tested using a KT-2 oil testing machine, white crystals formed on the surface of the facility. The values of friction coefficient are presented in Fig. 2 as a function of the temperature of the lubricant under study.

Table 1. Testing of lubricants with additives using a KT-2 oil testing machine

Semi-fluid lubricant	Before testing	250–300°C	Cold lubricant
Without additive			
Sulfo additive			
Phospho additive			
Hydroquinone			

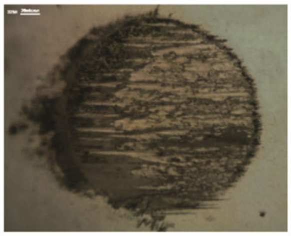
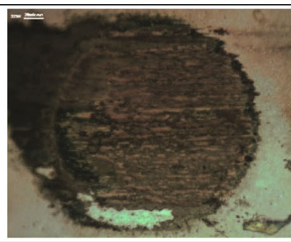
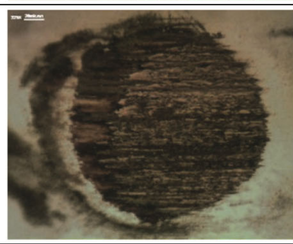
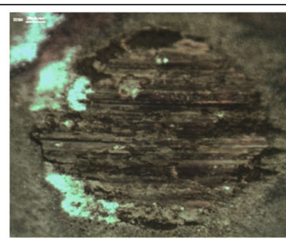
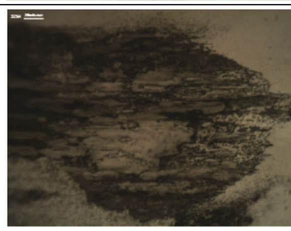
The figure shows that friction coefficient f_{fr} of the compound of a lubricant with an organophosphorus additive and hydroquinone fluctuates also at the melting temperature of the lubricant. The temperature dependence of the friction coefficient is unstable, which may be due to changes in chemical properties during testing. This assumption is partially confirmed by examining the surface of the locomotive wheel flange before (Fig. 3a) and after (Fig. 3b) tests using XRF.

The results can be explained as follows. Chrome atoms can penetrate into the space between the sulfur planes, which prevents moisture from penetrating the coating. MoS_2–Cr compounds retain the layered base structure of MoS_2, so they can form a stable transfer layer and provide good tribological properties due to the bulk structure of MoS_2, in which each MoS_2 layer consists of S–Mo–S stacks three atoms thick, in an atmosphere of high humidity. However, under all conditions, when the solubility limit of a compound is reached, Cr precipitates to form a discrete metal, resulting in poor tribological properties.

Under operating conditions, the temperature of the semi-liquid lubricant does not exceed 60°C; for this reason, wear tests were carried out on the flange surface on a friction machine, and the research results were analyzed in [6–9]. The test results are presented as dots in Fig. 4.

The results of testing locomotive wheel flange wear show that the lubricant with an organophosphorus additive exhibits the lowest wear value on the locomotive wheel flange surface, which is 110 μm. The flange

Table 2. Results of testing lubricants using a KT-2 oil testing machine

	260°C	300°C	Average size of wear spot D_w, μm
Without additive			202
Organo-phosphate additive			215
Hydroquinone			201
Sulfoorganic additive			245

wear with the semi-liquid lubricant was 180 μm; the value for the hydroquinone additive was 170 μm, and for sulfo compound, it was 150 μm. This effect of additives on the wear of the flange surface can be explained based on the previously proposed theoretical model of the wear rate of the wheel flange [10].

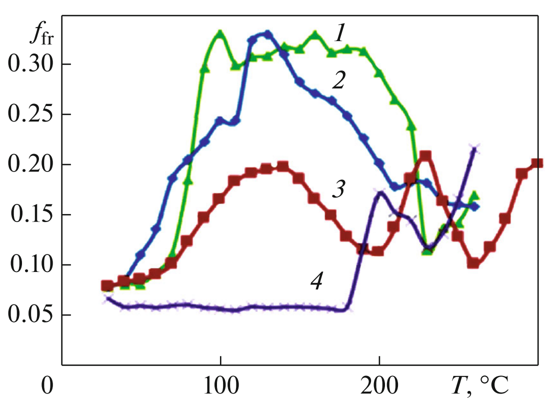


Fig. 2. Coefficient of friction as a function of test temperature of the semi-fluid lubricant: (*1*) without additive; (*2*) organophosphate additive; (*3*) hydroquinone; (*4*) sulfo compound.

According to [10], the formula for the wear rate is:

$$\upsilon = f_{fr} \frac{P\tau V}{L\eta K_C} I_{H_2} \times 10^{-9}, \quad (1)$$

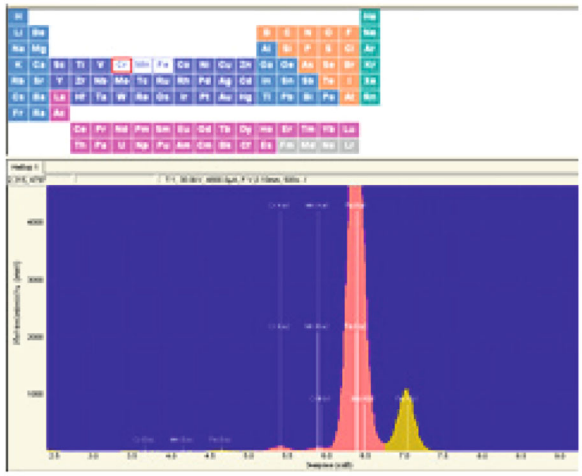
while it is clearly seen in [10] that the plot of the theoretical model lags behind the empirical points by a certain factor. We introduce coefficient χ into Eq. (1):

$$\upsilon = \chi f_{fr} \frac{P\tau V}{L\eta K_C} I_{H_2} \times 10^{-9} \quad (2)$$

and determine its value (Fig. 5).

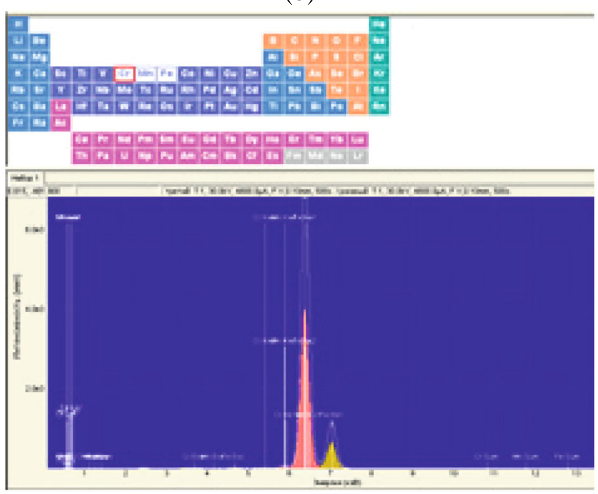
The values of coefficient χ probably correlate with the properties of the additives under study. However, an explanation of the numerical value of this coefficient requires additional research. Surfactants chosen as additives are adsorbed due to the fact that the polar parts of the molecules react with the active centers of the solid surface. The chemisorption process saturates these active centers with the formation of a protective

(a)



No.	Element	Concentration, %
1	Iron	99.08
2	Chrome	0.837
3	Manganese	0.0871

(b)



No.	Element	Concentration, %
1	Iron	99.70
2	Chrome	0.0741
3	Manganese	0.226

Fig. 3. XRF of wheel flange material: (a) before testing; (b) after testing.

film. The functional sulfo group in the additive and the long carbon skeleton provide the technological effects observed in surfactants. Due to the use of pentavalent phosphorus, cyclic structures of heteropolyphosphates can be formed.

CONCLUSIONS

(1) The use of an organophosphorus additive significantly reduces the rate of the release of diffusion-active hydrogen from $I_{H_2}^{puma} = 67$ to $I_{H_2}^{phos} = 8$ due to the influence of the active center of the molecule, which accepts protons.

The polar groups of the organophosphorus additive bind hydrogen, resulting in the formation of a multilayer matrix of organic molecules.

(2) The sulphonic compound is represented by layers in which the bonds of sulfur atoms are weak, thus allowing the film to slide and displace the layers along the path of friction. As a result, the resulting association oscillates between attraction and repulsion, which prevents contact between surfaces.

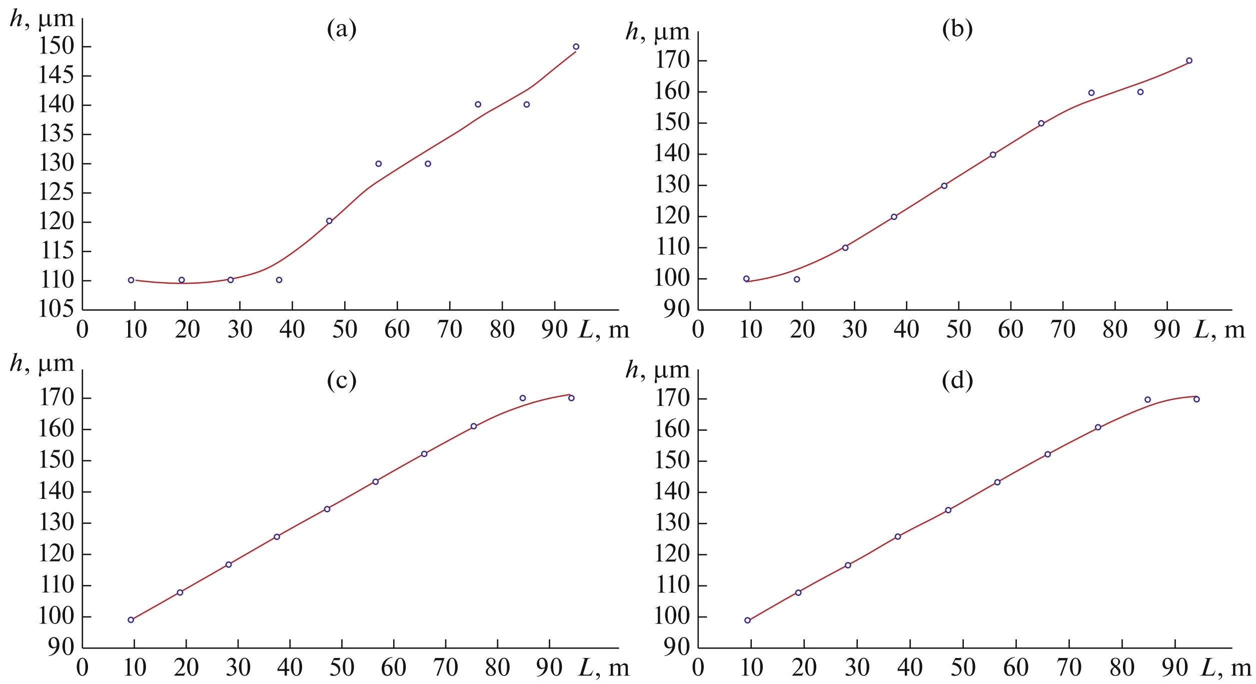


Fig. 4. Flange wear when using lubricant: (a) sulfo additive; (b) hydroquinone additive; (c) hosphor additive; (d) without additive.

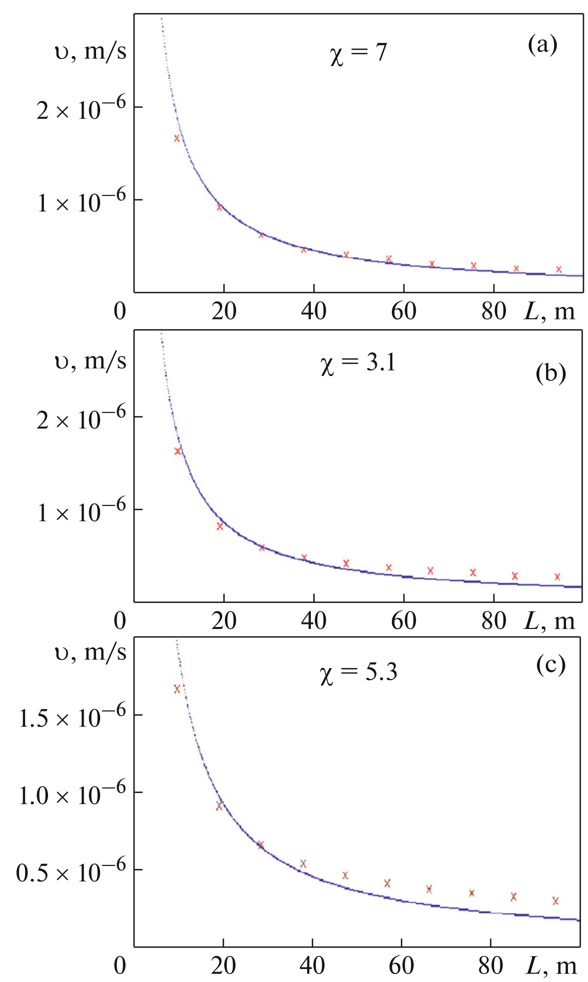


Fig. 5. Wear rate in using semi-fluid lubricant according to Eq. (2), straight line, and empirical data, points: (a) sulfo additive; (b) hydroquinone additive; (c) phospho additive.

(3) The introduction of hydroquinone increases the thermal stability of the lubricant.

NOTATION

P	is the (maximum) pressure of the rail flange on the curved section of the track
K_c	is impact strength of softer material (wheel flange)
η	is dynamic viscosity
τ	is shear stress in plastic lubricant
L	is the friction path
V	is the volume separated in the process of wear
υ	is the wear rate
I_{H_2}	is intensity of diffusion-active hydrogen release in the friction zone
f_{fr}	is the friction coefficient

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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