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Determination of the dynamic hardness of greases as a characteristic of deformation properties in a tribocontact

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Abstract

The efficiency of plastic oil is determined by the duration of its retention on the surface. Evaluation of the effectiveness of plastic lubricants depends on their mechanical properties. It is proposed to use the dependence of hardness on time when pressing a spherical indenter as one of the basic characteristics of the mechanical properties of plastic oils. The method of determining the function of oil hardness is based on the mechanics of contact interaction of a solid ball and a plane presented in this work, which has the property of creep according to the flow theory. One of the main methods of testing the deformation properties of plastic lubricants is to determine the number of penetrations. The number of oil penetrations is determined by the depth of indentation of the indenter; more informative for such a process is the ultimate pressure (hardness), which actually reflects the phenomenon of resistance to indenter indentation in the material. For uniform distribution of pressure under a spherical indenter the technique of construction of function of dynamic hardness of plastic materials is defined and on the basis of tests results of construction of dynamic hardness are received. Tests on contact creep of plastic lubricants are carried out, functions of dynamic hardness are received and the analysis of influence of character of change of dynamic hardness on wear processes in the presence of lubricants is carried out. To analyze the influence of deformation properties on the tribological properties of lubricants, comparative tests of the two above-mentioned types of lubricants on a four-ball friction device were performed. It was found that Litol-24 oil has the best wear resistance. The nonlinear period of running-in for this oil is practically absent that, obviously, under the given conditions of tests is connected with more stable in time deformation properties.

Keywords: grease, creep, penetration rate, dynamic hardness, test, wear.

Introduction

Plastic lubricants in the range of lubricants are the most common. Greases are thick oily products, which include: oil, thickener, solid carbon and various additives. A distinctive feature of plastic lubricants is that they are able, depending on working conditions, to have the properties of both solid and liquid substances. Under the action of small loads, lubricants behave like a solid body, can be held on vertical and inclined surfaces. The efficiency of plastic oil is determined by the duration of its retention on the surface. Evaluation of the effectiveness of plastic lubricants depends on their mechanical properties. Among the characteristics of mechanical properties, one of the most important is the shear strength of the oil. After the destruction of the frame, the oil begins to deform and flow like a liquid. Resistance to the flow of grease is characterized by viscosity. Typically, viscosity is determined at a single fixed strain rate. In the materials science of solids, the value of hardness is accepted as one of the mechanical characteristics. Hardness is the value of the average pressure under the indenter, which stabilizes the plastic deformation. In the mechanics of lubricants, the number of penetrations is analogous to the hardness of the lubricant. The number of penetrations is determined by pressing the cone into the flat surface of the grease and is measured in tenths of a millimeter for 5 seconds. With the help of the penetration number it is possible to estimate the effect of oil deformation at different temperatures. The disadvantage is that the number of penetrations is determined at one time point in the process that develops over time. At other time points of the penetration process, data on the hardness of lubricants can be obtained as opposed to those obtained at a holding time of 5 s. Also, the number of penetration of oil is determined by the depth of indentation of the cone. For metals, hardness is defined as the ultimate pressure, which actually reflects the phenomenon of resistance to indenter indentation in the material.

Therefore, it is proposed to use the dependence of hardness on time when pressing the spherical indenter as one of the basic characteristics of the mechanical properties of plastic lubricants.

The method of determining the function of oil hardness is based on the mechanics of contact interaction of a solid ball and a plane presented in this work, which has the property of creep according to the flow theory.

Literatuter review

The study of the tribological properties of greases in world science is given quite a lot of attention. Based on modern methods of experimental and theoretical research, new highly effective lubricants are synthesized. The behavior and properties of lubricants are modeled under various operating conditions, under heavy loads, high heat, extreme speeds.

In paper [1] three kinds of new conductive lubricating greases were prepared using lithium ionic liquids as the base oil and the polytetrafluoroethylene as the thickener. The conductivities and contact resistances of the prepared lubricating greases were investigated using the conductivity meter and the reciprocating ball-on-disk sliding tester. The results suggest that the prepared lubricating greases have high conductivities and excellent tribological properties. The high conductivities are attributed to ion diffusion or migration of the lithium ionic liquids with an external electric field, and the excellent tribological properties depend on the formation of boundary protective films.

The study [2] investigates grease film evolution with glass disc revolutions in rolling elastohydrodynamic lubrication (EHL) contacts. The evolution patterns of the grease films were highly related to the speed ranges and grease structures. The transference of thickener lumps, film thickness decay induced by starvation, and residual layer were recognized. The formation of an equilibrium film determined by the balance of lubricant loss and replenishment was analyzed. The primary mechanisms that dominate grease film formation in different lubricated contacts were clarified.

In [3] the grease film distribution under a pure rolling reciprocating motion is observed on a ball-disk test rig. It is found that the reciprocating motion reduces the accumulation of the thickener fiber gradually with time. The maximum film thickness forms around the stroke ends. The life of grease lubrication under a transient condition is far below that under steady-state conditions. When increasing the maximum entraining speed of the reciprocating motion to a certain value, during which the thickener fiber is not expected to accumulate under a steady-state condition.

In paper [4] the technique of relative optical interference intensity and simple numerical calculations were used to investigate the lubricating behavior of grease lubricant films. Experimental results indicate that at a same entrainment velocity of the inlet, the central film thickness under deceleration is larger than that under acceleration. The numerical method can also be used to explain the behavior of the grease lubricating film under non-steady state conditions.

Thermal-induced changes in the viscous and viscoelastic responses of lubricating greases have been investigated sn [5]. Small-amplitude oscillatory shear and viscous flow measurements were carried out on a model conventional lithium lubricating grease. Two different regions, below and above this critical temperature, in the plateau modulus versus temperature plot have been detected. From this thermal dependence, a much larger thermal susceptibility of the lubricating grease is apparent. The thermo-mechanical reversibility of this material has been studied by applying different combined stress–temperature protocols. The experimental results obtained have been explained on the basis of the thermo-mechanical degradation of the lubricating grease microstructure.

In [6] a methodology for continuous monitoring of grease degradation subjected to mechanical shearing is proposed. It is hypothesized that the mechanical degradation of grease is akin to the running-in process in a tribo-pair with both transient and steady-state regimes. From the results, a more effective method using the entropy generation rate is proposed for continuous monitoring of grease degradation. The proposed method is extended to estimate the time for a grease subjected to mechanical shearing to degrade to a lower grade. The efficacy of this method is demonstrated via long duration testing in a custom-built ball-bearing test apparatus.

The tribological properties of a lithium calcium complex grease based on calcium sulfonate complex and lithium complex greases are investigated in [7]. The tribological properties of the latter greases are compared using an Optimol SRV reciprocating friction and wear tester. The morphologies of the worn surfaces are traced by a scanning electron microscope (SEM) and the chemical states of several typical elements on the worn surfaces are examined by x-ray photoelectron spectroscopy (XPS). The results indicate that the new grease has a low friction coefficient and good wear-resisting ability.

The dependence of the colloidal stability, effective viscosity, penetration, and yield stress of low-temperature polymeric greases on the composition and characteristics of the dispersion medium was investigated in paper [8]. Various types of low-viscosity oil with known fractional and group composition were used as base oils. The effect of the concentration of the two-component thickener of high- or low-molecular polypropylene and the proportions of its components on the main physicochemical characteristics of the polymer greases was determined. The dependence of the structure and properties of the polymer greases on the concentration of lithium stearate was established.

Also, the scientific works of the authors [9-12] are devoted to various aspects of the use of greases in technical applications. At the same time, the analysis of studies has shown that little attention has been paid to the study of the deformation properties of greases under various conditions of tribological contact.

Contact mechanics of the process of interaction between the sphere and the viscoplastic lubricant

The direct formulation of the problem of the interaction of a solid ball of radius with a plane in a state of creep includes three relations (Fig. 1):

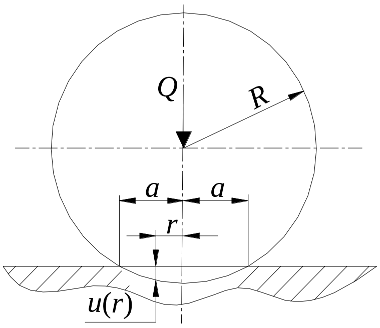

Fig.1. The scheme of contact of a ball and a viscoplastic plane

1) the model of constant creep of the lubricant material has the form:

$$\frac{du_c}{dt} = k_c \sigma^{m_c}\,; \tag{1}$$

2) the condition of continuity in contact can be represented as:

$$u_c(t) = \frac{a^2(t) - r^2}{2R}\,; \tag{2}$$

3) equilibrium condition in contact:

$$Q = 2\pi \int_0^a \sigma(t,r)\, r dr\,, \tag{3}$$

where $\sigma(t,r)$ is the time-dependent contact pressure distribution t;

$a(t)$ is the radius of the circular area of contact;

r is the radial coordinate.

Differentiating condition (2) and equating (1) we have:

$$\sigma(t) = \left(\frac{1}{k_c} \frac{a}{R} \frac{da}{dt} \right)^{\frac{1}{m_c}}, \tag{4}$$

it is obvious that the pressure is evenly distributed over the contact area.
Substituting this expression in condition (3), we obtain:

$$Q = 2\pi \int_0^a \left(\frac{1}{k_c} \frac{a}{R} \frac{da}{dt} \right)^{\frac{1}{m_c}} r dr\,. \tag{5}$$

After integration we obtain a differential equation with respect to the function $a(t)$:

$$\left(\frac{Q}{\pi} \right)^{m_c} = a^{2m_c} \frac{a}{k_c R} \frac{da}{dt}\,. \tag{6}$$

Solving this equation, we have:

1) at $a(t=0)=0$:

$$a(t)=\left[\left(2m_c+2\right)k_cR\left(\frac{Q}{\pi}\right)^{m_c}t\right]^{\frac{1}{2m_c+2}};\tag{7}$$

2) at $a(t=0)=a_0$:

$$a(t)=\left[\left(2m_c+2\right)\left(k_cR\left(\frac{Q}{\pi}\right)^{m_c}t+a_0^{2m_c+2}\right)\right]^{\frac{1}{2m_c+2}}.\tag{8}$$

With a uniform distribution of contact pressures we have:

$$\sigma\left(t\right)=\sigma_0\left(t\right)=\frac{Q}{\pi a^2\left(t\right)}.\tag{9}$$

The maximum displacement from creep is obtained at $r=0$:

$$u_{c0}(t)=\frac{a^2(t)}{2R}.\tag{10}$$

Example of calculating the size of the contact area when pressing the spherical indenter depending on (7).

Initial data:

1. Parameters of contact creep: $m_c=1,82$; $k_c=0,302$ МПа$^{\text{-mc}}$.
2. Spherical indenter radius $R=6,35$ mm.
3. Indenter weight $Q=1,9$ N.

Below are the results of the calculation obtained using the program MathCad.

t, min	2	3	7	17	37	67
$a(t)$, mm	1,47	1,58	1,83	2,14	2,46	2,73

Now suppose that the dependence of the radius of the contact $a(t)$ site on time is known from the experiment. It is necessary, using the solution of the direct problem, to determine the parameters k_c, m_c of the model of constant creep.

Consider the case of the initial zero contact site and present the experimental data in the form of a power approximation function:

$$a(t)=c_ct^{\beta_c}.\tag{11}$$

Substituting (11) into (7), we obtain:

$$c_c^{2m_c+2}t^{\beta_c\left(2m_c+2\right)}=\left(2m_c+2\right)k_cR\left(\frac{Q}{\pi}\right)^{m_c}t.\tag{12}$$

From the condition that this equation is executable for any values of the argument t follows:

$$m_c = \frac{1-2\beta_c}{2\beta_c}. \tag{13}$$

For the second parameter from (12):

$$k_c = \frac{c_c^{\frac{1}{\beta_c}} \beta_c}{R\left(\frac{Q}{\pi}\right)^{m_c}}. \tag{14}$$

The obtained results can be used to describe the contact creep of solid balls covered with thin deformed layers of lubricant, which is promising in creating tribomechanics of thin lubricating layers.

У випадку ненульової початкової площадки контакту () необхідно визначати параметри моделі повзучості при заданій експериментальній функції:

In the case of a nonzero initial contact site ($a_0 \neq 0$), it is necessary to determine the parameters of the creep model k_c, m_c given a experimental function:

$$a(t) = a_0 + a(t). \tag{15}$$

The solution of the problem is performed provided that the values of the two experimental points are known:

$$(a_1,\ t_1);\ (a_2,\ t_2) \tag{16}$$

at $a_0 < a_1 < a_2$; $0 < t_1 < t_2$.

The solution of the direct problem (7) for two points is presented in the form:

$$\left.\begin{aligned} a_1^{2m_c+2} - a_0^{2m_c+2} &= (2m_c+2)k_c R\left(\frac{Q}{\pi}\right)^{m_c} t_1, \\ a_2^{2m_c+2} - a_0^{2m_c+2} &= (2m_c+2)k_c R\left(\frac{Q}{\pi}\right)^{m_c} t_2. \end{aligned}\right\}. \tag{17}$$

Taking the ratio of equations, we obtain:

$$\frac{\alpha_1^{2m_c+2} - 1}{\alpha_2^{2m_c+2} - 1} = \frac{t_1}{t_2}, \tag{18}$$

where $\alpha_1 = \frac{a_1}{a_0}$; $\alpha_2 = \frac{a_2}{a_0}$. This nonlinear equation can be solved numerically.

Це нелінійне рівняння можна розв`язати чисельним методом

Method for determination and research of dynamic hardness of plastic materials

The procedure for determining the parameters of the creep function of the oil at zero contact area is as follows.

The initial parameters of the process of pressing the ball into the surface of the grease are selected:

R is the ball radius; Q is the load to ball.

The ball is pressed into the surface of the oil with the measurement of the maximum depth of pressing u_{c_0}.

Using formula (10), determine the radius of the area of contact of the ball with the surface of the oil:

$$a(t)=\left[2Ru_{c_0}(t)\right]^{\frac{1}{2}}. \tag{19}$$

The experimental dependence of the radius of the contact site on time is represented as a power function:

$$a(t)=c_c t^{\beta_c}. \tag{20}$$

Approximation parameters c_c, β_c are determined by the method of least squares.

Parameters m_c, k_c models (1) of oil creep are determined by formulas (13) and (14).

The procedure for determining the parameters of the dynamic hardness of the oil is as follows.

The hardness of the oil H_L or the average pressure on the ball on the oil side is determined by the relationship of type (9):

$$H_L(t)=\frac{Q}{\pi a^2(t)}. \tag{21}$$

If the value of the radius of the contact site is known from the experiment, the hardness is determined immediately by formula (21).

If parameters are known for oil m_c, k_c model of contact creep, the function of dynamic hardness is determined by substitution (7) in (21) at the initial zero contact area:

$$H_L(t)=\frac{Q}{\pi\left[(2m_c+2)k_c R\left(\frac{Q}{\pi}\right)^{m_c} t\right]^{\frac{1}{m_c+1}}}. \tag{22}$$

If it is necessary to compare the hardness of lubricants, functions are built $H_L(t)$.

When the non-zero contact area is set by the initial data R, Q and a_0. Conduct tests and obtain data for the function:

$$a(t)=a_0+a\ (t).$$

Two points are chosen for the function:

$$(a_1,\ t_1);\ (a_2,\ t_2)$$

and write for them equation (18) in the form:

$$\frac{\alpha_1^x-1}{\alpha_2^x-1}=\bar{t}_{12}, \tag{23}$$

де $x=2m_c+2$;

$\bar{t}_{12}=t_1/t_2$.

Numerically solve equations (23). The dynamic hardness of the oil is determined from the expression (22).

Investigation of dynamic hardness of plastic materials and its connection with wear

To implement the method of determining the parameters of contact creep of plastic materials, studies of bitumen and plasticine were performed by pressing a spherical steel indenter with a diameter of 12.7 mm and a weight of 190 g. The results of research and calculations of the parameters of the contact creep model are given in table. 4.1 with graphical interpretation in Fig. 2.

Table 1

Test results for contact creep and determination of dynamic hardness of plastic materials

Material	Time t, min	Depth indentation, u_c, mm	The size of the contact area a_c, mm	Parameters approximations		Parameters models contact creep		Hrdness function, MPa
				C_c,	β_c	m_c	k_c	
plasticine	1	0,11	1,18	1,297	0,177	1,82	0,302	$H_L = 0{,}361t^{--0{,}35}$
	2	0,18	1,5					
	3	0,23	1,7					
	7	0,29	1,9					
	17	0,36	2,14					
	37	0,47	2,44					
	67	0,55	2,64					
bitumen	1	0,4	2,22	2,403	1,803	1,77	8,943	$H_L = 0{,}106t^{--}_{0{,}36}$
	2	0,7	2,89					
	7	1,15	3,64					
	27	1,7	4,32					
	47	2,02	4,64					

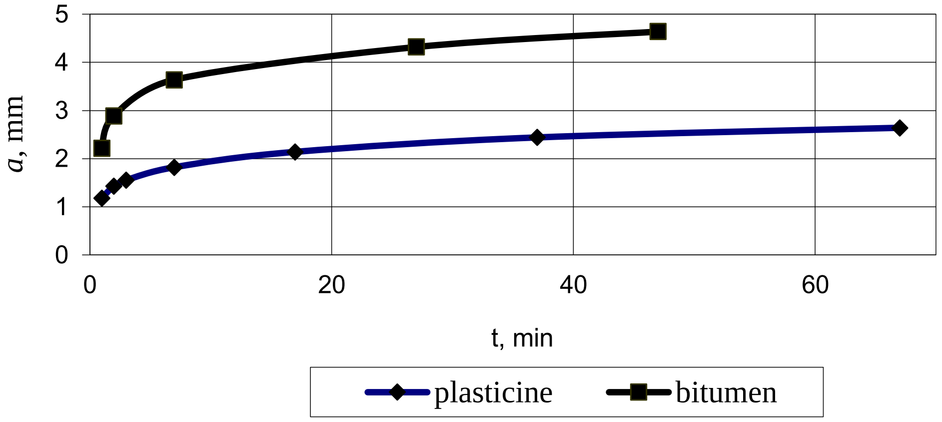

Fig. 2. The results of studies on contact creep

Results of tests of deformation properties of plastic oils by means of a ball with radius R= 15 mm are given in tab. 4 with graphical interpretation in Fig. 3.

Table 2

Test results of deformation properties of plastic lubricants

t, min	Ball, d = 30 mm, m = 150 g			
	Litol-24		Solidol C	
	a, mm	Δa, mm	a, mm	Δa, mm
0,08	12,75	0	9,86	0
0,6	12,99	0,24	10,09	0,23
2,6	13,15	0,4	10,30	0,44
7,6	13,36	0,61	10,51	0,65
17,6	13,64	0,89	10,71	0,85
47,6	13,89	1,14	10,9	1,04
107,6	14,07	1,32	10,99	1,13
227,6	14,2	1,45	11,09	1,23
407,6	14,44	1,69	11,18	1,32

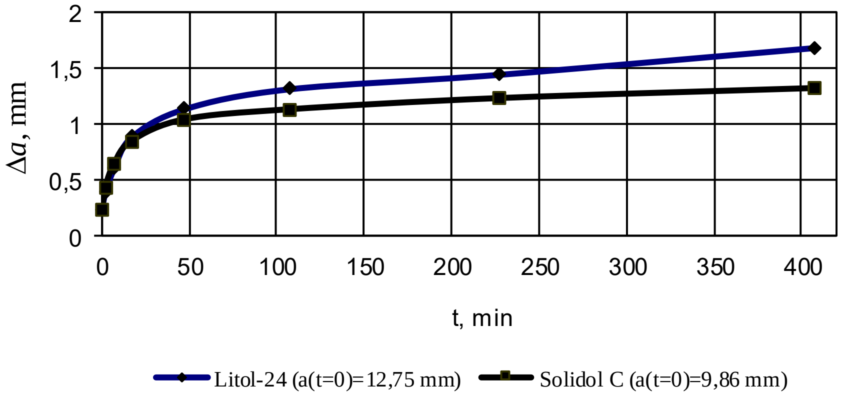

Fig. 3. The results of pressing the ball into the oil

The dependence (15) can be used to describe the process of pressing a cone and a ball with a non-zero initial contact pad.

As a result of processing the experimental data, the dependences for the contact site and the dynamic hardness when pressing the ball indenter into the surface of the plastic oil were obtained (Table 3).

Table 3

The results of determining the dynamic hardness for lubricants

Type of indentor	Solidol C	Litol –24
Steel ball, $R = 15$ mm	$a(t) = 9{,}86 + 0{,}334t^{0{,}258}$	$a(t) = 12{,}75 + 0{,}315t^{0{,}299}$
Dynamic hardness, MPA	$H_L(t) = Q/\pi a^2(t) = 0{,}48/a^2(t)$	

According to the obtained results, graphical dependences of hardness for two types of investigated plastic lubricants are constructed, shown in fig. 4.

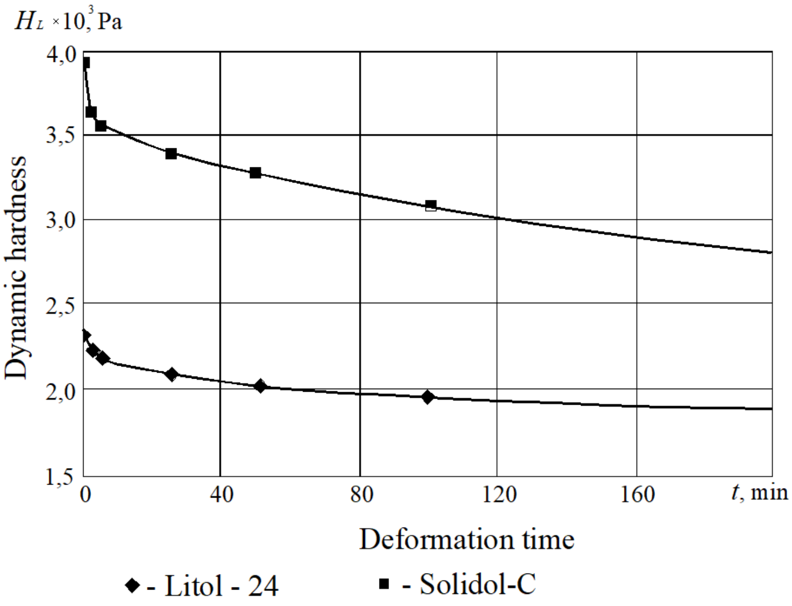

Fig. 4. Dynamic hardness of lubricants during deformation

Analysis of the obtained graphs shows that Litol - 24 oil has a lower dynamic hardness, but is characterized by more stable indicators over time. With a durability of almost 3 hours, the hardness of Solidol - 24 decreased by 40%, while Litol-24 decreased by only 20%, which indicates better stability of the load-bearing capacity of Litol -24 over time. The obtained dependences for the characteristic of dynamic hardness allow to analyze the processes of deformation of lubricating layers of different lubricants under the action of applied loads.

To analyze the influence of deformation properties on the tribological properties of lubricants, comparative tests of the two above-mentioned types of lubricants on a four-ball friction device were performed. (V = 0.45 m/s; N = 350 N). As a result, the dependences of wear on the test time are obtained (Fig. 5).

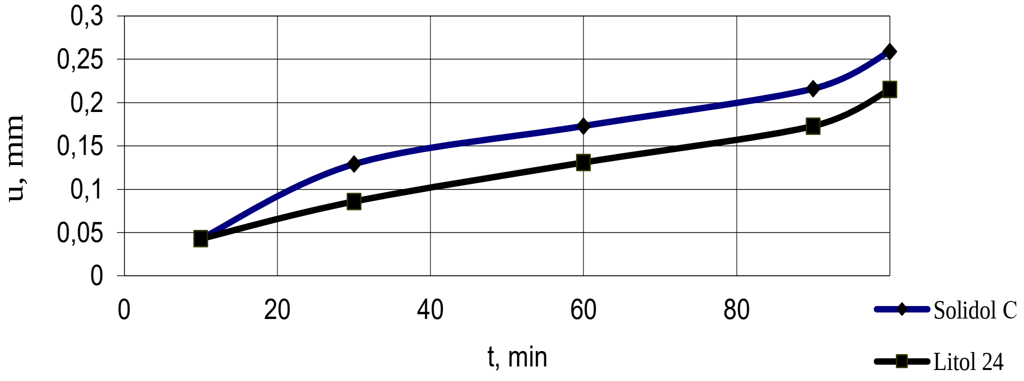

Fig. 5. Results of tribological tests of lubricants

It was found that Litol-24 oil has the best wear resistance. The nonlinear period of running-in for this oil is practically absent that, obviously, under the given conditions of tests is connected with more stable in time deformation properties.

Conclusions

1. One of the main methods of testing the deformation properties of plastic lubricants is to determine the number of penetrations. The essence of this method is to measure the depth of indentation of the conical indenter in the surface of the lubricant sample. The main disadvantages of this method are the following:

- the number of penetration is determined at one time point of the indenter indentation process, when measurements at other time points will be obtained data on the deformation of lubricants opposite to those obtained at a holding time of 5 s;
- the number of penetration of oil is determined by the depth of indentation of the indenter; more informative for such a process is the ultimate pressure, which actually reflects the phenomenon of resistance to indenter indentation in the material.

2. A more informative characteristic of the deformation properties of plastic materials is proposed - a function of dynamic hardness, which shows the dependence of the pressure of resistance to indenter indentation on the time of deformation.

3. To establish the analytical dependence for dynamic hardness, the mechanics of contact interaction of a rigid indenter in the form of a ball with plastic lubricant, which has the property of creep, is considered. Solved direct and inverse problems and recommendations for their use.

4. For uniform distribution of pressure under a spherical indenter the technique of construction of function of dynamic hardness of plastic materials is defined and on the basis of tests results of construction of dynamic hardness are received.

5. Tests on contact creep of plastic lubricants are carried out, functions of dynamic hardness are received and the analysis of influence of character of change of dynamic hardness on wear processes in the presence of lubricants is carried out.

6. The offered characteristic of dynamic hardness and a method of its definition allows to estimate and compare deformation and tribological properties of various plastic materials at certification control, operation and creation of new types of oils..

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Диха О.В., Старий А.Л., Дитинюк В.О., Диха М.О. Визначення динамічної твердості консистентних мастил як характеристики деформаційних властивостей у трибоконтакті

Ефективність роботи пластичного мастила визначається тривалістю її збереження на поверхні. Оцінювання ефективності пластичних мастил залежить від їхніх механічних властивостей. Пропонується як одну з базових характеристик механічних властивостей пластичних мастил застосовувати залежність твердості від часу при втисненні сферичного індентора. Метод визначення функції твердості мастила ґрунтується на представленій в цій роботі механіці контактної взаємодії твердої кульки та площини, що має властивість повзучості за теорією течії. Одним з основних методів випробувань деформаційних властивостей пластичних мастильних матеріалів є визначення числа пенетрації. Число пенетрації мастила визначається глибиною вдавлювання індентора; більш інформативним для такого процесу є граничний тиск (твердість), який реально відображає явище опору вдавлювання індентора в матеріал. Для рівномірного розподілу тиску під сферичним індентором визначена методика побудови функції динамічної твердості пластичних матеріалів і на основі випробувань отимані результати побудови динамічної твердості. Проведені випробування на контактну повзучість пластичних мастил, отримані функції динамічної твердості і проведений аналіз впливу характеру зміни динамічної твердості на процеси зношування в присутності мастильних матеріалів. Для аналізу впливу деформаційних властивостей на трибологічні властивості мастил були проведені порівняльні випробування двох вказаних вище типів мастил на чотирикульковому приладі тертя. Встановлено, що мастило Литол-24 має кращі зносостійкі показники. Нелінійний період припрацювання для цього мастила практично відсутній, що, очевидно, за даних умов випробувань пов`язано з більш стабільними в часі деформаційними властивостями.

Ключьові слова: консистентне мастило, повзучість, число пенетрації, динамічна твердість, випробування, зношування