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DYNAMIC VISCOSITY OF THE LUBRICANT AND ITS EFFECT ON STEEL MATERIALS WITH BORON

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In this work, the regularities of the change in the shear strength of the adhesive bond τ_0 and the piezoelectric coefficient β in the metal systems "12Kh2N4 (45KhN2MFA) - steel 45 + B", "12Kh2N4 (45KhN2MFA) - steel 45 + VS" were obtained during physical modeling of the shear of surfaces of small-sized samples and changes in dynamic viscosity environment of their interaction with the use of additional equipment of the SMTs-2 friction machine. It has been established that boriding and boron carburizing of the surface of steel 45 leads to the absence of adhesion to the surfaces of steels 12Kh2N4 and 45KhN2MFA in certain ranges of normal pressures, at which τ_0> 0 and the dynamic viscosity of liquid and grease. It was found that the parameter τ_0 when lubricating surfaces is determined to a greater extent for the system "12X2H4 - steel 45", and partially for borating steel 45 and low values of dynamic viscosity μ = 0.027 Pa•s. With an increase in the dynamic viscosity of the liquid phase of the lubricant in the "12X2H4 - steel 45" system, there is a tendency to an increase in the value of τ0. It was found that the absence of modification of steel 45 with boron and boron carbide predetermines the independence of the piezoelectric coefficient from the viscosity of the liquid lubricant and the shear rate. Boriding and boron carburizing steel 45 predetermines an increase in the piezoelectric coefficient by an average of 1.6 times with an increase in dynamic viscosity from 0.027 Pa•s to 0.19 Pa•s at a shear rate of 10.16±0.8. At shear rate = 5.08±0.6 mm/s, the piezoelectric coefficient is relatively constant in the systems under study. With the transition to contact through a grease lubricant, there is an ambiguous manifestation of the rate of change of the piezoelectric coefficient.

Keywords: *piezo coefficient, dynamic viscosity, lubricant, shear rate, tangential strength*

Introduction

Forecasting the resource of mechanisms of mechanical engineering objects presupposes the presence of certain initial data. In this case, the main quantity is the wear rate of the surfaces of materials, which is determined both experimentally and theoretically. So, for example, when calculating the service life of a gear pair, it is necessary to know not only the geometric parameters of the engagement, but also the parameters of the adhesion properties and fatigue of the contacting surfaces. This is especially important when measures are proposed to modify the working surfaces to improve the physical and mechanical properties of metals. The existing structural alloy steels 12Kh2H4, 45KhH2MFA, high-quality carbon steel 45 are widely used for the manufacture of a wide range of mechanical engineering parts, including gears, gear shafts of gear drives for various purposes. Undoubtedly, the presence of numerical values of the parameters of the adhesion properties of the listed jointly working metals will determine the accuracy of the calculations performed, and the possible surface modification of one of them will expand the information on the nature of its influence on the manifestation of these parameters. Based on the above, the establishment of regularities in the manifestation of the parameters of adhesion properties in systems of structural metals seems to be an urgent scientific and fundamental task considered in tribology.

1. Review of previous publications, setting the goal of the work

The technology of surface modification of steel 45 by boriding and boron cementation is proposed, which predetermines the change in both the phase composition of the surface structures and their hardness [1-3]. Boriding of steel refers to the saturation of steel with the element boron. After such saturation, the surface layer with a size of about 0.3 mm becomes hardened with a hardness of 18000-20000 HV. The industry uses boron in solid, liquid and gaseous states. The disadvantage of the method is the fragility of the

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surface layer, which can break off after impact. Boron cementation of steel is the process of simultaneously saturating its surface with elements of boron and carbon. This process is carried out at a temperature of about 1200 K using boron carbide. As a result of boron cementation, the hardness increases by 1.2-1.4 times and relative wear resistance in comparison with the carburizing process.

In [4], the regularities of the change in the shear strength of the adhesive bond τ0 and the piezoelectric coefficient β in the metal systems "steel 45 - 40X", "steel 45 + B - 40X", "steel 45 + BC - 40X" were obtained during physical modeling of the shear between small samples in the environment of lubricants I-20A, Wolf 10W-40, TAD-17i, Litol-24 with distinctive dynamic viscosities using additional equipment of the SMTs-2 friction machine. At the same time, the features of the manifestation of the parameters of the adhesion bond depending on the shear rate have been established. The results obtained are typical for systems of materials in which alloyed structural steel 40X is a constant element. This steel has one alloying element chromium, which predetermines the amount of surface energy, due to a greater extent to the chemical element - iron.

Steels 12Kh2N4, 45KhN2MFA can be alternative steel 40Kh structural metals, for example, as discussed above, for the manufacture of gears. Moreover, they have a different content of chemical elements, and, accordingly, surface energy (surface tension [5, 6]), which will affect the formation of adhesive interaction in contact with steel 45 when it is modified with boron and boron carbide. Moreover, the hardness of steels 12Kh2N4, 45KhN2MFA is less than steel 40Kh. From this, it is evident that it is necessary to perform not only an assessment of the manifestation of adhesion parameters in systems of metals with steels 12Kh2N4, 45KhN2MFA, but also to establish their change depending on the decrease in the hardness of one of the elements of the friction pair, in this case it is a direct pair.

The aim of the work is to establish the regularities of changes in the parameters of the adhesive bond in the systems of materials "steel 45 – 45KhN2MFA", "steel 45 + B - 45KhH2MFA", "steel 45 + VS - 45KhH2MFA", "steel 45 - 12Kh2H4", "steel 45 + B - 12Kh2H4 "," steel 45 + BC - 12Kh2H4 "in the physical modeling of the shift between small-sized samples in the environment of lubricants with distinctive dynamic viscosities using additional equipment of the SMTs-2 friction machine. Based on the above, this work seems to be a continuation of the complex of studies begun in [3, 4, 7].

2. Research methodology

The parameters of the adhesive bond were evaluated using an SMTs-2 friction machine with additional equipment in accordance with the procedure described in [7]. In this case, movable samples - disks were made of steels 12Kh2N4, 45KhN2MFA, and fixed pads in the form of triangular-shaped segments of steel 45 with surface modification with boron and boron carbide, i.e. the same samples were used as in [4]. To estimate the pressure in the contact zone and the tangential shear strength, we used the average values of the contour areas, which were determined from the indentations. The modeling of the manifestation of the properties of the lubricating medium was carried out using the same lubricants as in [4]. The following lubricants were applied to the surface of the samples:

- industrial oil I-20A (GOST 20799-88), dynamic viscosity at 40 ºC μ = 0.027 Pa•s;
- transmission oil TAD-17i (GOST 23652-79), dynamic viscosity at 50 ºC μ = 0.106 Pa•s;
- semi-synthetic motor oil Wolf 10W-40 API SL/SF, dynamic viscosity at 40 ºC μ = 0.19 Pa•s;
- Litol-24 grease (GOST 21150-2017), dynamic viscosity at 50 ºC μ = 8 Pa•s.

This choice of lubricants determined, firstly, different values of the dynamic viscosity for the liquid state of aggregation of the lubricating medium, and secondly, the presence of a consistent medium. This makes it possible to take into account the possible contact interaction of the surfaces of the teeth of gears of various gears, for example, in mechanical drives of machine tools, transmission units for cars and tractors, gearboxes of hand-held power tools, etc.

To assess the parameters of adhesion without lubricant, the surfaces were thoroughly degreased with gasoline "Kalosha".

3. Research results and their discussion

As a result of processing the tribograms of the shear surfaces of a stepwise loaded contact in the considered systems of materials, statistical data were obtained, which are summarized in tables 1, 2. Analysis of the data obtained indicates the following. First, the parameter τ0 is determined only:

- in the absence of lubricant for the system "45KhN2MFA - steel 45". In this case, exclusively boronization of the surface of steel 45 leads to a slight increase in the value of τ0 from 3.58 MPa to 5.6 MPa;

- when lubricating surfaces to a greater extent for the system "12Kh2H4 - steel 45" in the absence of surface modification of steel 45, as well as when it is boriding and low values of dynamic viscosity μ = 0.027 Pa•s. In this case, with an increase in the dynamic viscosity of the liquid phase of the interaction lubricant, a tendency to an increase in the value of τ_0 is observed. To a lesser extent, this parameter manifested itself for the system "45KhN2MFA - steel 45" again with dynamic viscosity μ = 0.027 Pa•s, but without modification of steel 45. On the whole, the results obtained confirm the thesis given in [5] on the structural sensitivity of the adhesive parameters. The manifestation of the adhesive interaction parameter τ0 in the absence of lubrication can be explained by the ratio of the hardness of the interacting surfaces. According to the research conditions, H12Kh2H4 <H45KhH2MFA <H45, and H45 <H45 + B <H45 + BC.

Table 1. Parameters of approximation of experimental data for the system of materials "45KhN2MFA - steel 45 (+ B, + VS)" in the environment of lubricants

Parameter	Steel 45				Steel 45+B				Steel 45+BC			
Lubricant	I-20	TAD-17и	Wolf 10W40	Lithol -24	I-20	TAD-17и	Wolf 10W40	Lithol -24	I-20	TAD-17и	Wolf 10W40	Lithol -24
Piezo coefficient *β*	$\tau = 0{,}11p + 3{,}58$ -				$\tau = 0{,}05p + 5{,}6$ $\tau = 0{,}14p - 0{,}24$				$\tau = 0{,}24p - 18{,}9$ $\tau = 0{,}38p - 33{,}3$			
	0,12	0,13	0,12	0,12	0,15	0,13	0,17	0,12	0,11	0,1	0,14	0,15
	-	-	-	-	0,24	0,21	0,21	0,17	0,14	0,14	0,16	0,13
Tangential strength τ_0, MPa	2,02	> 0 at *p*≈23 MPa	>0 at *p*≈2 MPa	>0 at *p*≈23 MPa	>0 af *p*≈30 MPa	>0 at *p*≈26 MPa	>0 at *p*≈58 MPa	>0 at *p*≈38 MPa	>0 at *p*≈23 MPa	>0 at *p*≈18 MPa	>0 at *p*≈52 MPa	>0 at *p*≈23 MPa
	-	-	-	-	>0 at *p*≈40 MPa	>0 at *p*≈48 MPa	>0 at *p*≈46 MPa	>0 at *p*≈40 MPa	>0 at *p*≈24 MPa	>0 at *p*≈18 MPa	>0 at *p*≈56 MPa	>0 at *p*≈88 MPa

Note. 1. The upper row of values at a shear rate $\upsilon_1 = 10.16 \pm 0.8$ mm/s, the lower one at $\upsilon_2 = 5.08 \pm 0.6$ mm/s.
2. The equation of the form is given for a system without lubricant.

Table 2. Parameters of approximation of experimental data for the system of materials "12Kh2H4 - steel 45 (+ B, + BC)" in the environment of lubricants

Parameter	Steel 45				Steel 45+B				Steel 45+BC			
Lubricant	I-20	TAD-17и	Wolf 10W40	Lithol -24	I-20	TAD-17и	Wolf 10W40	Lithol -24	I-20	TAD-17и	Wolf 10W40	Lithol -24
Piezo coefficient *β*	$\tau = 0{,}36p - 13{,}44$ -				$\tau = 0{,}2p - 10{,}5$ $\tau = 0{,}2p - 5{,}56$				$\tau = 0{,}33p - 32{,}3$ $\tau = 0{,}37p - 33{,}8$			
	0,1	0,11	0,1	0,15	0,11	0,18	0,17	0,1	0,18	0,16	0,18	0,13
	-	-	-	-	0,15	0,15	0,15	0,14	0,11	0,14	0,14	0,12
Tangential strength τ_0, MPa	8.3	4,8	10,7	>0 at *p*≈24 MPa	1,0	>0 at *p*≈30 MPa	>0 at *p*≈54 MPa	1,0	>0 at *p*≈42 MPa	>0 at *p*≈44 MPa	>0 at *p*≈60 MPa	>0 at *p*≈5 MPa
	-	-	-	-	1,21	>0 at *p*≈17 MPa	0,5	>0 at *p*≈17 MPa	0,1	>0 at *p*≈62 MPa	>0 at *p*≈58 MPa	>0 at *p*≈38 MPa

Note. 1. The upper row of values at a shear rate $\upsilon_1 = 10.16 \pm 0.8$ mm/s, the lower one at $\upsilon_2 = 5.08 \pm 0.6$ mm/s. 2. The equation of the form is given for a system without lubricant.

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From which it follows that in each of the contact options, the parameter τ_0 is extrapolated back after the manifestation of plastic, elastic-plastic and elastic deformation of the microprofiles of metal surfaces. Such interaction can be estimated in accordance with the relaxation theory of adhesion, which considers deformation processes, the appearance of internal stresses in the thinnest surface layers and their subsequent relaxation [8]. In this case, the deformable metal layers have different thicknesses with one interface. When the load is removed during elastic deformation, the dimensions are restored, i.e., there is a sufficiently large supply of internal mechanical energy in the near-surface layers. From which it follows that such an energy reserve is capable of forming, among other things, the action of surface forces of adhesive interaction. While the supply of such energy can be critically maximum only up to a certain value from the point of view of a possible increase in the surface energy of one of the components of the system. This is exactly what happened when modifying steel 45 with boron carbide, i.e. it is possible to change the mechanism of adhesive interaction by the nature of its appearance.

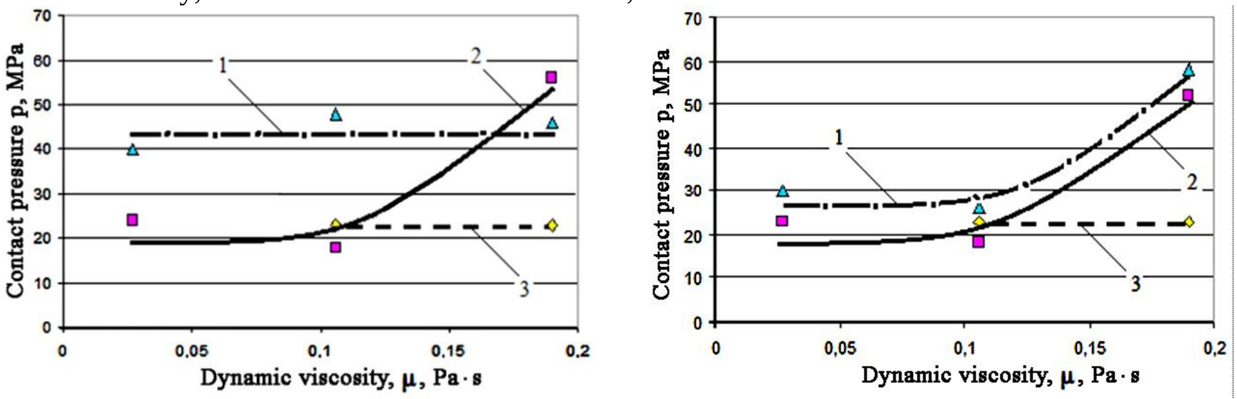
The manifestation of the parameter τ_0 of adhesive interaction in a lubricating medium can be explained by a large adsorption decrease in surface strength (Rebinder effect) for a less solid component of the system of materials, which predetermines the formation of the manifested large adhesion forces with a harder surface. Those. the less solid surface of the component of the metal systems under study seems to be more susceptible to penetration of the less viscous liquid phase of the lubricant, which manifested itself for the system "12Kh2H4 - steel 45". Based on the above, the considered interaction can be estimated in accordance with the theory of weak boundary layers [8].

In accordance with this theory, "weak" boundary layers with physicochemical properties that differ from those of the underlying layers are formed in the contact zone. In this case, it is the "weak" layers that determine the strength of the adhesive bond. In this case, the deformable metal layers have different thicknesses, but already with two interfaces. The first interface is formed by the elements "body (rotating disk, material 12Kh2H4, 45KhH2MFA) - a near-surface layer of a lubricant with bulk properties". The second surface is "a near-surface layer of a lubricant with bulk properties - a counterbody (fixed block, material steel 45"). From which it follows that the shear fracture mechanism can be not only cohesive [8], that is, within the adsorbed and deformed molecules of the lubricant (transition regions), but also mixed, taking into account the destruction of bonds along the interfaces. The latter is explained by the characteristics of the microprofiles of the contacting surfaces, which causes uneven deformation of the lubricant molecules distributed between them.

Second, boriding and boron carburizing of the surface of steel 45 leads to the absence of adhesion to the surfaces of steels 12Kh2N4 and 45KhN2MFA in certain ranges of normal pressures, at which $\tau_0 > 0$. This range is determined by the upper limit of the mechanical pressure p. In general, the following holds:

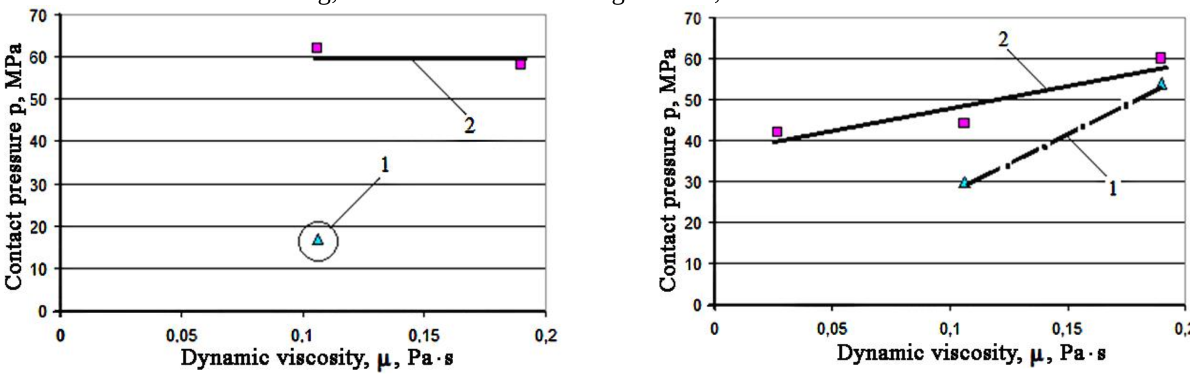
- a larger range of pressures is typical for the system "12Kh2H4 - steel 45", which, for example, at a shear rate of $\upsilon_1 = 10.16 \pm 0.8$ mm/s for liquid lubricant is from 0 to 42 MPa when borated steel 45, and from 0 to 48 MPa with its boron carburizing. For grease, this range is much smaller - from 0 to 17 MPa for boriding, and from 0 to 5 MPa for boron carburizing. At the same time, a twofold decrease in the shear rate leads to a decrease in the average range in a liquid medium by 2.5 times during boriding, and an increase in the range by 1.25 times for a liquid lubricant during boron cementation;
- a smaller range of pressures is typical for the system "45KhN2MFA - steel 45", which, for example, at a shear rate of $\upsilon_1 = 10.16 \pm 0.8$ mm/s for a liquid lubricant is from 0 to 38 MPa when boriding steel 45, and from 0 to 31 MPa with its boron carburizing. However, for grease, this range appeared from 0 to 38 MPa for boriding, and from 0 to 23 MPa for boron carburizing. At the same time, a twofold decrease in the shear rate leads to an insignificant increase in the average range in a liquid medium during boriding, and its equality for a liquid lubricant during boron cementation. For grease, the range was preserved within the same boundaries during boriding as in a liquid medium, and its increase by 3.8 times during boron cementation.

For a more detailed and visual assessment of the dependence of the upper pressure limit on the change in the dynamic viscosity of the liquid lubricant in accordance with the data of table 1, 2, graphical dependencies are built, Fig. 1, 2. From Figure 1 it follows that in the material system "45KhN2MFA - steel 45", the change in the dynamic viscosity of the liquid lubricant, starting from 0.11-0.12 Pa • s, predetermines an increase in the pressure of the beginning of the manifestation of adhesion forces during boron cementation of steel 45 and the shear rate of 5.08 ± 0.6 mm/s. The same takes place when it is borated and boron-cemented, but at a shear rate of 10.16 ± 0.8 mm/s. At the same time, the intensity of its growth remains unchanged. The viscosity in the range from 0.01 to 0.11 Pa•s does not affect the change in the beginning of the manifestation of adhesion between the surfaces during boriding and boron-carburizing steel 45. The viscosity also does not affect the beginning of the manifestation of adhesion between the surfaces of the systems under study, even in the absence of modification, steel 45.



a) b)

Fig.1. Influence of dynamic viscosity on the manifestation of adhesion in the system of materials "45KhN2MFA - steel 45" by pressure in contact: a - at $\upsilon_2 = 5.08 \pm 0.6$ mm/s; b - at $\upsilon_1 = 10.16 \pm 0.8$ mm/s; 1 - steel 45 when boriding; 2 - with boron carburizing steel 45; 3 - steel 45 without modification.



a) b)

Fig.2. Influence of dynamic viscosity on the manifestation of adhesion in the system of materials "12Kh2H4 - steel 45" by pressure in contact: a) - at $\upsilon_2 = 5.08 \pm 0.6$ mm/s; b) - at $\upsilon_1 = 10.16 \pm 0.8$ mm/s;
1 - steel 45 when boriding; 2 - with boron carburizing steel 45

From Figure 2 it follows that in the system of materials "12Kh2H4 - steel 45" only at a shear rate of 10.16 ± 0.8 mm/s, a change in viscosity causes a linear increase in the pressure of the beginning of the manifestation of adhesion forces during boron carburizing of steel 45 throughout the simulated range. The same effect of viscosity occurs during boriding steel 45, but in the range from 0.11 to 0.2 Pa s, however, the increase in values occurs with greater intensity.

The obtained and described results on the parameter τ_0 generally indicate the ambiguity and peculiarity of the manifestation of adhesion between the studied surfaces of steels, activated for interaction by the supply of external mechanical energy of high mechanical pressures, excess surface energies due to the introduction of additional chemical elements during the modification of steel 45 and components of the used lubricating media. At the same time, it should be noted the effect of a short-term structural change in liquid lubricants on the contour contact areas during their compression, since the design pressures are sufficiently high. The pressures in the zone of frictional interaction ranged from 80 MPa to 260 MPa. Due to the complexity and versatility of the components of these processes and the limited information on their course, this issue is not discussed in the work and remains open.

Thirdly, the parameter β has a simpler and rather informative calculated manifestation. For a more visual assessment, graphical approximations of the trends in the change in the piezoelectric coefficient in the considered systems of materials when modeling the shear rate in the range of dynamic viscosity of liquid lubricants are shown in Figs. 3, 4. The analysis of the presented dependencies in Fig. 3, 4 indicates the following. First, the absence of modification of steel 45 with boron and boron carbide predetermines the independence of the piezoelectric coefficient from the viscosity of the liquid lubricant and the shear rate.

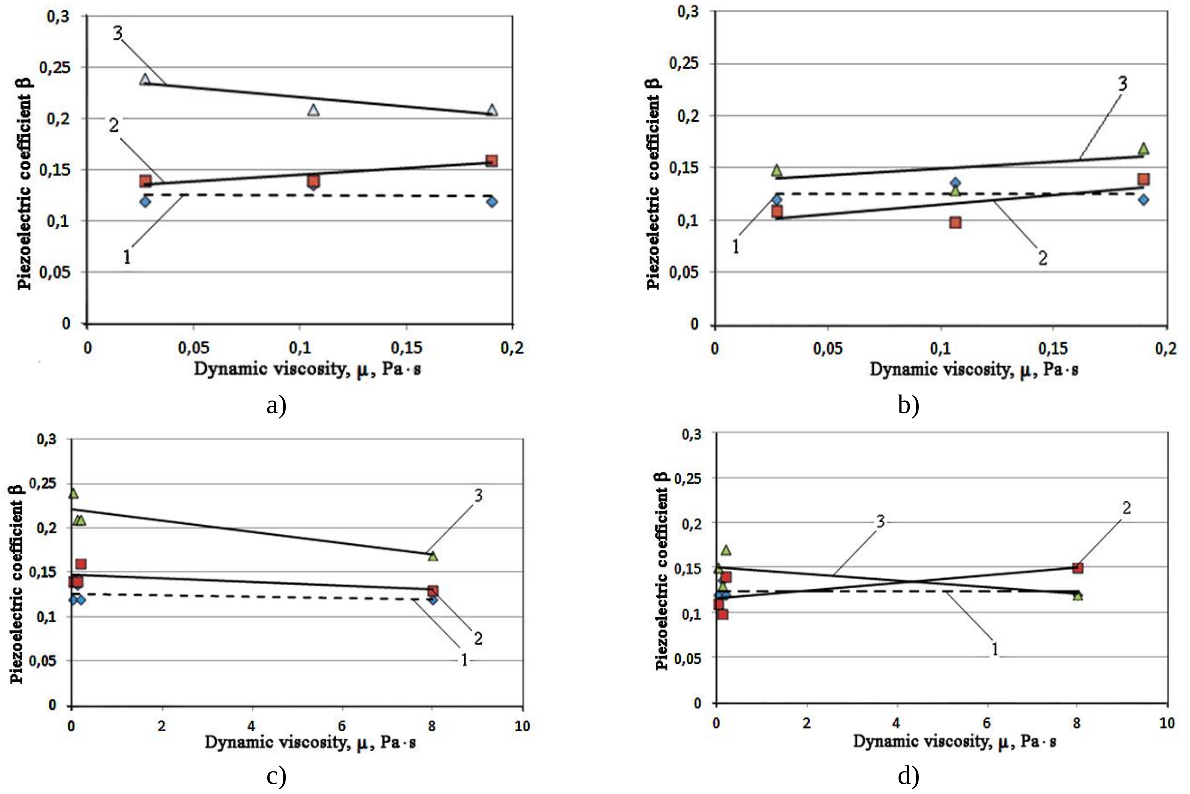


Fig.3. Influence of dynamic viscosity in the range of liquid (a, b) lubricant and taking into account the range of consistent state (c, d) on the change in the piezoelectric coefficient of adhesive bond in the material system "45KhN2MFA - steel 45": a, b - at = 5.08 ± 0.6 mm/s; b, d - at = 10.16 ± 0.8 mm/s; 1 - steel 45 is not modified; 2 - "steel 45 + BC"; 3 - "steel 45 + B".

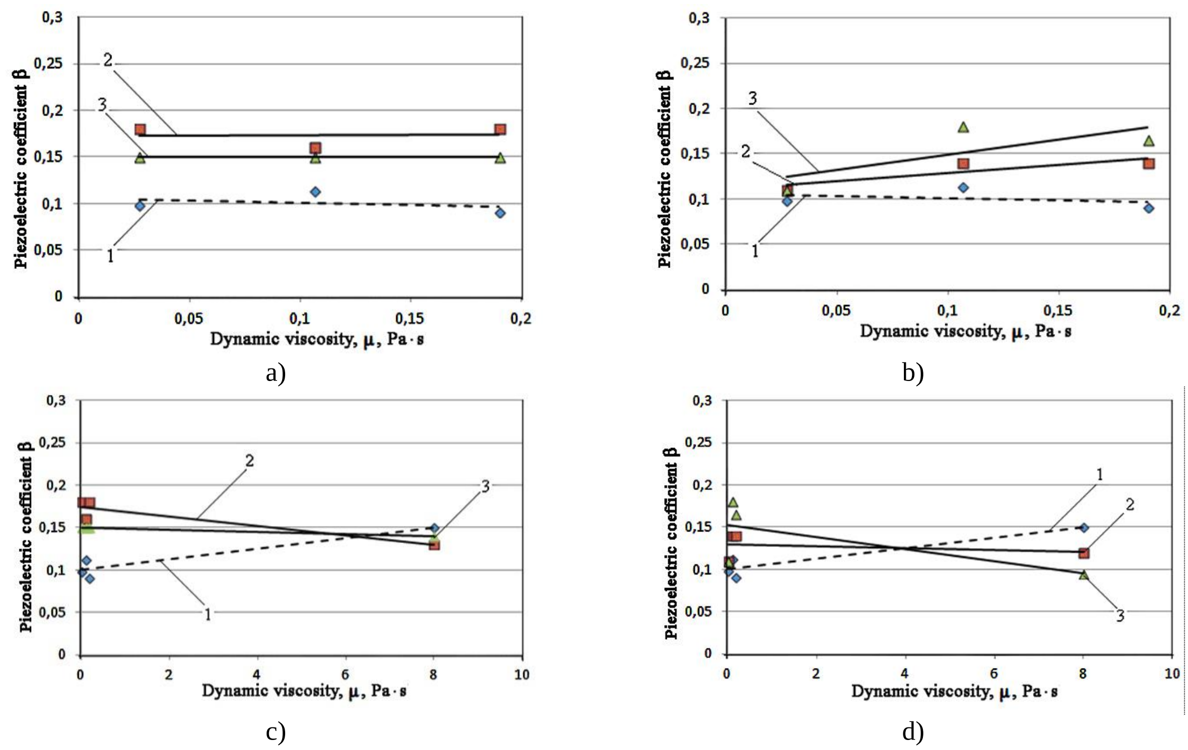


Fig.4. Influence of dynamic viscosity in the range of liquid (a, b) lubricant and taking into account the range of the consistent state (c, d) on the change in the piezoelectric coefficient of adhesive bond in the material system "12Kh2H2 - steel 45": a, b - at = 5.08 ± 0.6 mm/s; b, d - at = 10.16 ± 0.8 mm/s; 1 - steel 45 is not modified; 2 - "steel 45 + BC"; 3 - "steel 45 + B"

In the simulated ranges of viscosity and shear rate, the increment of the piezoelectric coefficient values is zero. The exception is the system "12Kh2H2 - steel 45". For this system of metals with the transition to a grease lubricant, the rate of increase in the piezoelectric coefficient is 0.0064 $(Pa·s)^{-1}$.

At the same time, the average statistical values of the piezoelectric coefficient are: for the system "12Kh2H2 - steel 45" in the viscosity range from 0.001 Pa • s to 0.2 Pa•s β = 0.1 ± 0.003, for the system "45KhN2MFA - steel 45" β = 0, 12 ± 0.003. From which it seems obvious that the intensity of the increase in the strength of the adhesive bond in the system "45KhN2MFA - steel 45" is 1.2 times higher.

For the system "12Kh2H2 - steel 45 + B (BC)" with a shift of 5.08 ± 0.6 mm/s, the rate of decrease of the piezoelectric coefficient is 0.005 $(Pa•s)^{-1}$. From which it follows that modification with boron and boron carbide predetermines a less intense increase in the strength of the adhesive bond of the investigated metal surfaces.

Conclusion

The results obtained in the work revealed the features of the manifestation of the adhesive bond parameters in the investigated metal systems when simulating changes in dynamic viscosity in the range from 0.027 Pa•s to 8 Pa•s.

The constructed graphic patterns and the parameters of their mathematical approximation made it possible to determine the direction of the processes of adhesive interaction of the surface of 45 steel modified with boron and boron carbide with steels 12Kh2N2, 45KhN2MFA through lubricating formations compacted by contact pressure with distinctive gradients of dynamic viscosity.

It has been established that the boriding and boron cementation of steel 45 predetermines the expansion of the range of working normal pressures in lubricating media, excluding the manifestation of the adhesive friction component, and in contact with steel 45KhN2MFA upwards.

The data obtained can be used, firstly, as reference values of the adhesive bond parameters to substantiate the possibilities of increasing the reliability of the operation of friction pairs during shear, and secondly, when calculating the service life of a gear pair, in which the gears will be made from the studied systems of materials.

The direction of further research is proposed to consider the study of the nature of the relationship between the manifestation of the established parameters τ_0 and β and the surface energies of the contacting surfaces of the metal systems under consideration.

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