ISSN 2079-1372 Problems of Tribology, V. 31, No 1/119-2026, 6-15

Problems of Tribology
Website: http://tribology.khnu.km.ua/index.php/ProbTrib
E-mail: tribosenator@gmail.com

DOI: https://doi.org/10.31891/2079-1372-2026-119-1-6-15

Tribochemistry of damage to metal joints during fretting corrosion

V.V. Shevelya[*] 0000-0002-5462-3524, **V.P. Oleksandrenko** 0000-0002-2404-2104, **O.V. Dykha** 0000-0003-3020-9625, **K.S. Sokolan** 0000-0002-3513-8312
Khmelnytskyi National University, Ukraine
[*]*E-mail: valeriy.shevelya@gmail.com*

Received: 30 November 2025: Revised 12 December 2025: Accept: 10 January 2026

Abstract

The patterns of fretting wear of a number of structural materials and galvanic coatings were researched, taking into account their mechanical and physicochemical properties. The influence of the composition of the gas environment (air, oxygen) on the intensity of fretting wear was assessed, as well as the contact load with the corresponding temperature recording in the friction zone. Data were obtained indicating the possibility of low-amplitude fretting of metals in an air environment along with the oxidative processes of electrochemical corrosion. The physicochemical prerequisites for the initiation of electrochemical processes in the zone of vibrational contact during the formation of an ultradisperse oxide layer, which becomes a catalyst for the accelerated chemisorption of oxygen and air moisture in radical and ion-radical forms, are considered. As a result, according to the electronic theory of adsorption and catalysis on semiconductors (oxides), contact phenomena begin to develop through the mechanism of autocatalytic corrosion. After a latent period of oxide accumulation, conditions are created for electrochemical processes that contribute to corrosion-fatigue failure of mating surfaces. The results of the study expand existing ideas about the nature of corrosion processes during partial and mixed sliding, focusing on the possibility of using traditional methods of electrochemical protection to increase the fretting resistance of friction units operating under vibration conditions.

Keywords: fretting wear, friction coefficient, fretting resistance, adsorption, corrosion, electrochemistry, chemical-thermal treatment

Introduction

In many industrial equipment devices, machines, and instruments, the cause of failure is often fretting corrosion, which affects nominally stationary or low-movement couplings during their relative oscillatory motion with a small amplitude [1-4]. Such joints include, for example, bolted, splined, and threaded connections; gear couplings and lock joints; press and hot fits on shafts of discs, bearings, and wheel hubs; pipe fittings, etc. [5-10]. The cause of relative slippage in connections is vibration of the entire structure or the connection performing its working functions. In addition to loss of fit due to fretting wear, destruction due to fretting fatigue poses a great danger.

It is generally accepted that fretting wear develops as a result of the synergistic superposition of a number of contact phenomena, including adhesion (bonding), abrasive wear, delamination (surface delamination), contact fatigue, and oxidation processes [11-14]. In addition to the strength and viscoelastic properties of structural materials, their resistance to fretting wear is also influenced by chemical resistance, which, in combination with the corrosive activity of the external environment and the physicochemical properties of wear products (oxides), determines the specific vulnerability of metal joints [15-17]. However, the tribochemistry of fretting resistance of friction contact under vibration conditions has not been sufficiently studied. In particular, the problem of the influence of the nature of contact corrosion processes responsible for the degradation and destruction of mechanical tribosystems during “dry” fretting in an air working environment remains relevant. While the development of chemical corrosion (oxidation) during metal fretting in an air atmosphere is undisputed, there is no consensus regarding electrochemical corrosion. It is known that the occurrence and rate of electrochemical corrosion depend mainly on atmospheric humidity and temperature [18]. However, the question of how these factors affect the electrochemical corrosion mechanism under fretting conditions remains open due to conflicting

experimental data. In some cases, an increase in air humidity or temperature increased fretting wear, while in others it decreased it. For example, studies in which the rate of fretting wear decreased with increasing temperature [2,19] indicate the possibility of electrochemical corrosion. However, on the other hand, there is data showing that when the temperature was increased to 300°C, the wear rate during impact fretting increased by an order of magnitude compared to room temperature [20].

Experiments in which a more than 10-fold decrease in the fretting fatigue life of metal in air compared to vacuum was observed [4] support the idea that electrochemical corrosion can develop during fretting in a normal air environment. Earlier [21], when studying the fretting resistance of joints consisting of a number of alloys in contact with steel 45, it was shown that the more positive the electrode potential of the alloy relative to steel 45, the less it wore out. Simultaneously with the increase in the nobility of the alloy, the wear of the counterbody – steel 45, increased. This effect was associated with the accumulation of highly dispersed oxides in the vibration contact zone, which actively adsorbed moisture and oxygen from the air, resulting in electrochemical corrosion superimposed on the chemical corrosion (oxidation) process.

Thus, the role of electrochemical processes in fretting corrosion of nominally stationary or low-mobility joints remains controversial and requires further research. Obviously, much depends on the nature of the friction pair materials, the amplitude-load operating mode, the composition and properties of wear products, and the stage of fretting process development. The limited experimental data complicates the modeling of the physicochemical processes leading to the failure of the mechanical tribosystems under consideration.

The **aim of this work** is to research the contribution and role of chemical and electrochemical corrosion in the wear process of metal friction pairs under low-amplitude fretting conditions.

Research materials and methodology

The fretting resistance (fretting wear) of armco iron and a number of steels with mechanical and physicochemical properties acquired as a result of heat treatment under standard conditions (Table 1) was researched.

Table 1

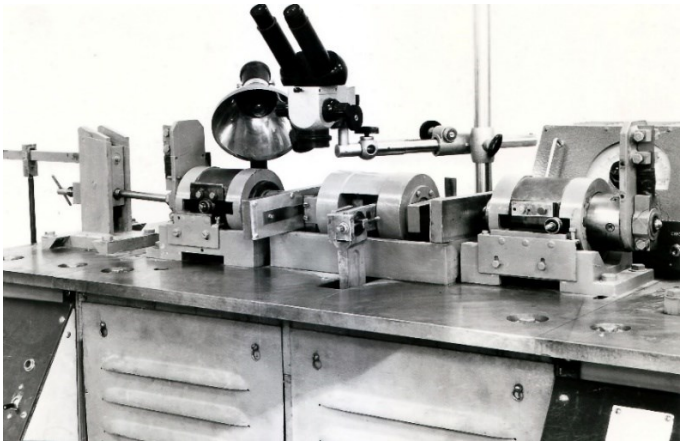
Researched steels and their mechanical properties

Mechanical properties	Steel 45	ShKh15	DI-3A	16KhGTA	38KhA	30KhGSA	40KhNMA
$\sigma_в$. MPa	1450	2200	1100	1050	1050	1200	1090
σ_{-1}. MPa	550	800	540	600	500	650	490
HV	420	770	430	310	460	440	500
φ. V	-0.35	-0.36	-0.37	-0.38	-0.38	-0.40	-0.30

The fretting wear of a number of electrolytic coatings on steel 45 (Zn, Cd, Pb, Sn, Ag) was also studied.

The tests were carried out on an МФК friction machine (Fig. 1*a*) in accordance with GOST 23.211-80 [23], according to which fretting corrosion was caused in a flat ring contact during oscillatory-rotational motion around the axis of the bushing end face (movable sample) relative to the end face of a stationary fixed cylindrical sample made of the material under study (Fig. 1*b*).

In all cases, the material of the moving sample (bushing) was steel 45, hardened and tempered to *HV* = 600; at the same time, the weight wear of both the stationary and moving samples was evaluated with simultaneous control of the friction coefficient. In addition to air, oxygen was used as a gas medium, which was blown through the gas chamber of the experimental setup, after which its flow was set with a slight excess pressure before the experiment.



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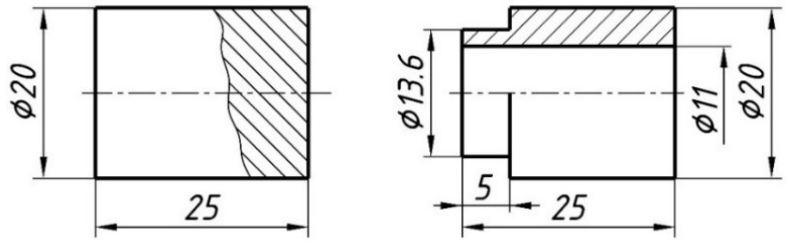


***b*)**

Fig. 1. General view of the МФК setup (*a*) and samples (*b*) for testing metals for fretting corrosion

To evaluate the electrochemical activity of the studied steels, the steady-state electrode potentials in a 3% NaCl solution (φ, V) were determined relative to a standard hydrogen electrode, and a potentiostatic method was used to record the anodic polarization curves.

Research results and discussion

Given the vibrational, alternating nature of contact interaction that causes fretting corrosion, it is natural to assume that the main cause of metal surface destruction under fretting conditions (apart from adhesion and abrasive wear) is fatigue and corrosion processes. Obviously, the degree of structural damage to metals, as well as the role of chemical factors, can vary significantly depending on the loading parameters (number of fretting cycles, specific load, sliding amplitude, oscillation frequency), the aggressiveness of the external environment, and the stage of development of the fretting process. It can be expected that the intensity of fretting wear at a certain stage of damage will be related to the degree of dispersion of the surface layers in the contact zone. The disordered ultradisperse structure of the metal acquires increased chemical and electrochemical activity in the presence of a suitable environment.

Fig. 2 compares the fretting wear kinetics of armco iron and 45 steel, which reveals the following pattern: up to a certain critical number of test cycles, armco iron wears out faster than steel, and above that number of cycles, steel wears out more intensively. It can be assumed that in the initial stages of fretting, when corrosion processes are not yet sufficiently developed, the wear resistance of the material is determined by its contact strength. Naturally, steel 45 is more wear-resistant under these conditions due to its greater ability to resist plastic deformation. The greater wear of steel compared to iron in the subsequent stages of fretting corrosion is obviously associated with the activation of chemical processes in the contact zone, which should lead to a change in friction conditions. Indeed, as fretting corrosion develops, a monotonic decrease in the friction coefficient is observed for both materials (Fig. 3), and by the time the friction regime has stabilized, when the chemical factor begins to manifest itself more significantly, the degree of decrease in the friction coefficient for steel 45 is always greater due to the increased effectiveness of the shielding action of corrosion products.

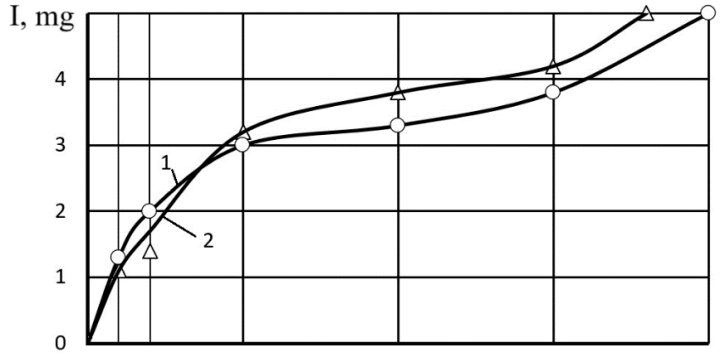


Fig. 2. Dependence of fretting wear of armco iron (1) and steel 45 (2) on the number of loading cycles: A = 0,05 mm; P = 25 MPa; f = 25 Hz

With an increase in the number of test cycles, steel wear increases compared to armco iron, which may indicate the development of a corrosion process in the contact zone that is different from chemical oxidation. It is quite likely that the wear products concentrated between the contacting surfaces initiate a series of corrosion processes, and in the later stages, the development of electrochemical corrosion.

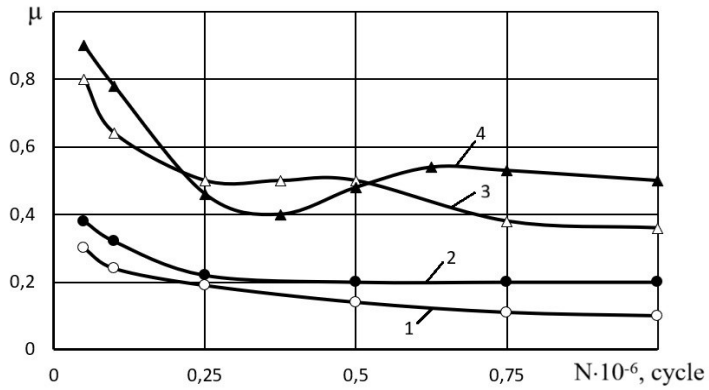


Fig. 3. Change in the friction coefficient during the development of fretting corrosion of steel 45 (1.3) and armco iron (2.4): 1,2 - *P* = 10 MPa; 3,4 - *P* = 50 MPa

From an electrochemical point of view, steel 45, unlike armco iron, has a large amount of cathodic impurities (cementite), which create an additional amount of microgalvanic couples. The effect of such impurities depends on the nature of the corrosion process control [18]. With cathodic control, cathodic impurities will increase the corrosion rate: the more cathodic impurities in the metal (steel 45) and the greater the potential difference between the cathodic and anodic components of the metal, the higher the corrosion rate. Thus, it can be concluded that at the beginning of fretting corrosion, chemical (gas) corrosion processes predominate, and with an increase in the number of loading cycles, electrochemical processes may occur in the friction zone.

Comparative tests in air and oxygen (no moisture removal) of steel 45 (Fig. 4) demonstrated the possibility of electrochemical processes developing under fretting corrosion conditions.

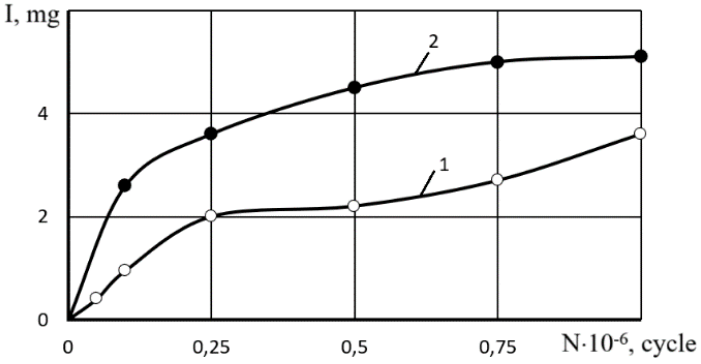


Fig. 4. Dependence of fretting wear of steel 45 on the number of loading cycles in air (1) and in oxygen (2): *P* = 10 MPa; *A* = 0,05 mm; *f* = 25 Hz

At the very beginning of fretting corrosion, when the chemical factor manifests itself in the predominant oxidation processes, with an excess of oxygen in the external environment, a material with increased chemical activity (45 steel) is more susceptible to fretting wear. Obviously, at this stage, due to the formation of an oxide layer, the mechanical factor plays a secondary role, since friction conditions are facilitated. The latter is evidenced by a decrease in the friction coefficient during tests in oxygen compared to air at the stage of wear stabilization. On steel, which is more chemically active than armco iron, oxide films form and break down more quickly in oxygen, which contributes to the earlier development of electrochemical processes.

In electrochemical corrosion with oxygen depolarization, when the cathodic process is the controlling factor, an increase in the concentration of the cathodic depolarizer (oxygen) in the friction zone intensifies corrosion. With an increase in load, the development of electrochemical processes begins at earlier stages of fretting corrosion, since the corrosion rate with oxygen depolarization (which occurs in our case) is usually determined by the rate of oxygen diffusion to the corroding metal surface [18]. As the contact load increases, the access of atmospheric oxygen to the contact zone becomes more difficult, thereby significantly increasing the concentration polarization of oxygen, i.e., cathodic control occurs earlier. Under such conditions, an increase in the concentration of oxygen (cathodic depolarizer) in the environment leads to an observable increase in the destruction of contacting surfaces due to the activation of electrochemical processes. In addition, it should be noted that as the load increases, the processes of formation and subsequent destruction of primary oxide films accelerate, so that the oxide layer between the contacting surfaces forms more quickly. Accordingly, electrochemical corrosion begins to develop earlier due to the active adsorption of moisture and oxygen by oxides.

Fig. 5 shows the change in the intensity of fretting wear of the metals under study depending on the specific load. The number of cycles ($N = 3 \cdot 10^5$) corresponding to the stabilization of wear values, when corrosion processes prevail and the behavior of the material is significantly determined by its chemical activity, was taken as the basis for testing.

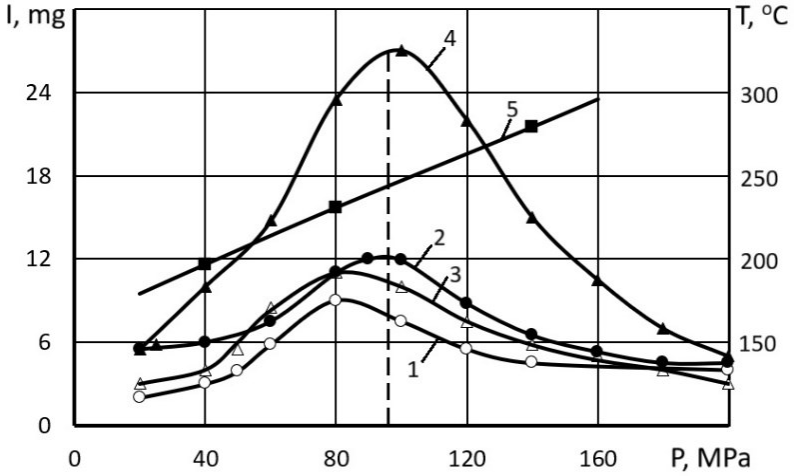


Fig. 5. Dependence of fretting wear of armco iron (1,2) and steel 45 (3,4) on contact load in air (1,3) and in oxygen (2,4); 5 – change in contact temperature: $N = 3 \cdot 10^5$ cycles; A = 0,05 mm; f = 25 Hz

The dependence of wear on specific load is parabolic in nature: the amount of wear increases up to a load of about 80 MPa, and then decreases. It should be emphasized that the sliding amplitude remained constant at all load levels. Obviously, at specific loads corresponding to the ascending branches of the characteristics, the oxidizing environment enters the friction zone relatively more easily. The reduction in wear at loads above critical values may be due, firstly, to the difficulty of access of the oxidizing environment to the contact zone and the activation of the setting process, and secondly, to the increase in temperature at the contact, which can significantly worsen the conditions for the formation of a corrosive environment. Indeed, the effect of reducing fretting wear of the materials under study upon reaching a certain critical contact pressure (80-100 MPa) can be associated with an increase in temperature to 230-250°C recorded in the contact zone (using a thermocouple), which is precisely the temperature limit for the removal of adsorbed moisture and oxygen [24]. Dehydration of the oxide surface leads to a decrease in adsorption activity.

A comparison of the rate of deterioration of iron and steel 45 depending on the specific load during tests in air and oxygen (see Fig. 5) shows that the lower wear of these materials in air compared to oxygen could be explained (given the higher friction coefficient for air) by the greater intensity of adhesive bonding and mutual transfer of metal from one surface to another. Considering that armco iron has reduced hardness, the adhesion factor for this material should be most significant. However, the wear of armco iron in both environments differs little, while steel 45 deteriorates more in oxygen and to a greater extent the higher the pre-critical load. Obviously, in this case, the tendency of the material to electrochemical corrosion plays a decisive role. In fact, for chemically inactive armco iron, an increase in the oxygen content in the external environment does not significantly intensify fretting wear. At the same time, for a more corrosion-active material (steel 45), the role of an environment with a strong oxidizing effect becomes decisive in the destruction of the joint.

Obviously, if contact is made between materials of the same name, electrochemical corrosion should be caused by microgalvanic couples (structural heterogeneity, different crystal orientation, structural imperfections, etc.). It is natural to assume that electrochemical processes will manifest themselves more clearly if contact is made between dissimilar materials that differ in their electrochemical properties (macrogalvanic couple). When a corrosion-active environment arises in the contact zone, electrochemical processes should develop according to the mechanism of contact corrosion [18].

To verify this possibility, a study was conducted, the first stage of which examined the fretting corrosion of 45 steel in contact with electrolytic coatings (Zn, Cd, Pb, Sn, Ag). The counterbody (movable sample) was 45 steel – hardened.

The following pattern was established: the more noble the surface in contact with the steel, the less wear that surface experienced and, in turn, the more fretting wear the steel itself experienced (Fig. 6).

It can be seen that the coatings with which steel 45 worked are arranged in an electrochemical series in order of increasing positivity of their electrode potential. Coatings with a more negative electrode potential than steel 45 (Zn, Cd), while protecting the steel from corrosion, are themselves intensively destroyed: steel itself begins to play a similar role when it is in contact with tin and silver. It is noteworthy that at a relatively low specific load (P = 10 MPa), steel samples in contact with zinc showed not only no wear, but also an increase in weight.

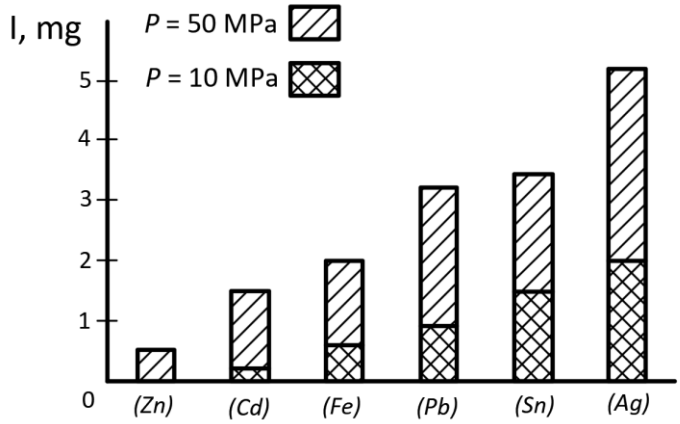


Fig. 6. Dependence of fretting wear of steel 45 on the nature of metals in contact with it, arranged in an electrochemical series: $N = 5 \cdot 10^5$ cycle; $A = 0{,}05$ mm; $f = 30$ Hz

Considering that under normal test conditions (air), intermetallic contact in fretting corrosion is quickly disrupted due to the formation of an oxide layer, and also taking into account the observed strong dependence of the intensity of destruction on the composition of the external environment (oxygen concentration, humidity), preference should be given not to a series of contact potential differences, but to a series of normal electrode potentials. In the second stage, the effect on fretting wear of 45 series steels with different mechanical and physicochemical properties acquired as a result of hardening heat treatment using the technology commonly accepted for each material and having a similar electrode potential (Table 1) was researched. For each of these materials, the tangent of the slope of the anodic polarization curve (Tafel constant - *b*), which characterizes the activation overpotential of electrochemical dissolution, was additionally determined using a potentiostat [18]. It turned out that the higher the Tafel constant of the material in contact with steel 45, the more the steel wears out, and vice versa (Fig. 7).

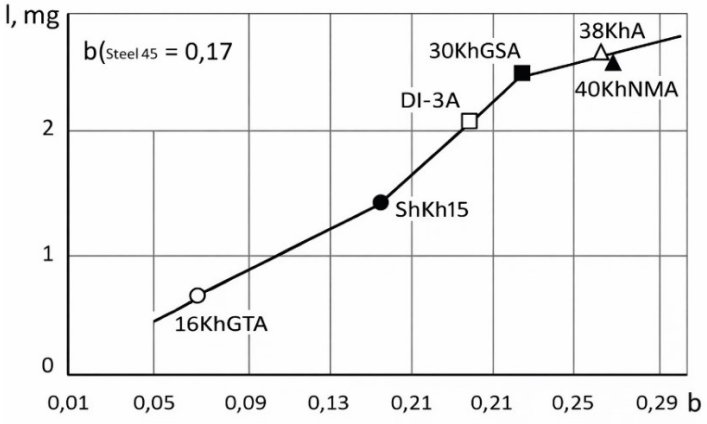


Fig. 7. Fretting wear of steel 45 depending on the value of the Tafel constant (*b*) of the counterbody: $N = 5 \cdot 10^5$ cycles; $P = 10$ MPa; $A = 0{,}05$ mm; $f = 30$ Hz

The patterns observed indicate that electrochemical factors play a significant (and sometimes leading) role in low-amplitude fretting [22]. The peculiarity of the conditions of interaction between contacting surfaces during fretting corrosion (vibration, low sliding amplitude, preservation of wear products—oxides—in the friction zone) contributes to the occurrence of specific topochemical reactions, which, in turn, change the nature of contact. The transition of the surface layers of metal in the initial stage of fretting corrosion to an amorphous or near-amorphous (ultradisperse) state accelerates surface oxidation reactions [2]. The resulting degradation products in the form of oxides, which are usually semiconductors, can give the process an autocatalytic character (wear products accelerate oxidation and corrosion) [24]. Moreover, the fine grinding of oxides increases the free surface area and the number of active centers, which contributes to the activation of adsorption and catalysis processes. The catalytic effect of oxides manifests itself in the acceleration of oxygen and moisture adsorption, with the adsorbed molecules transforming into a more easily activated form under the influence of surface forces or available free valences. Indeed, the nature of molecules in the gas phase and in the chemisorbed state is different. According to the electronic theory of adsorption and catalysis on semiconductors, adsorbed molecules undergo significant deformation and weakening of intramolecular bonds, as well as involve free carriers (electrons and holes) in the

chemisorption bond. The localization of free carriers on the adsorbed particle converts it into a radical or ion-radical form, which has high reactivity due to the acquisition of a charge state (O_2^-, O^-, H_2O^+, etc.). Moreover, the adsorption of a molecule may be accompanied by its dissociation with the formation of new valence-saturated and unsaturated compounds. Thus, in chemisorbed water molecules in a state of coordination bond with the oxide surface, deformation results in the weakening of O-H bonds [24]. In this case, the water molecule is protonated, and at elevated temperatures it can even lose a proton and turn into an OH group. Protonated water molecules adsorbed by the coordination mechanism are new centers for subsequent water adsorption by the mechanism of hydrogen bond formation. During the adsorption of an oxygen molecule as a result of the transfer of two electrons from two negative ions of the oxide crystal lattice, the double bond of the molecule may break. Subsequently, the localization of the hole or the recombination of the hole and the free electron of the oxide may convert the oxygen atom into a reactive radical form. In addition to acquiring anomalous properties, adsorbed water and oxygen molecules change the electrophysical properties of the oxide and, in particular, charge its surface. Chemosorbed oxygen molecules, being acceptors, localize free electrons, charging the semiconductor surface negatively. The adsorption of H_2O molecules (donor particles) charges the surface positively and increases the electrical conductivity of the oxide. The opposite nature (donor-acceptor) of the adsorbed water and oxygen molecules increases the adsorption activity of the oxide surface.

The processes of chemisorption of water and oxygen on oxides create conditions for the emergence of an electrochemical environment between contacting surfaces, capable of giving the fretting process the character of catalytic corrosion, when the mobility of surface metal atoms increases, resulting in the rapid redistribution of the substance between different areas of the surface. In particular, the activation polarization of the metal should decrease (the ionization overvoltage will decrease). The catalytic action of oxides manifests itself in the emergence of reactive radical and ion-radical forms of chemisorption on them. Indeed, our qualitative reaction to peroxide compounds in the products of fretting corrosion of steel, bronze, etc. (based on the reaction with solutions of starch in water and potassium iodide in acetic acid) showed the presence of peroxide forms, probably in the form of the ion radical O_2^-. Charged forms of chemisorption and induced reaction flows should activate electrochemical processes during fretting corrosion. Thus, the emergence of an accelerating field during oxygen adsorption (O_2^-, O^-) reduces the ionization overvoltage of the metal (facilitating the anodic process). The presence of radical forms of adsorbed moisture H_2O^+ and the course of topochemical reactions via the self-oxidation mechanism should accelerate the cathodic process. The oxides formed are capable of acting as a cathode, which, together with the emergence of elements of differential aeration (which is particularly favored by the conditions of the contact under study), creates additional prerequisites for the development of electrochemical corrosion.

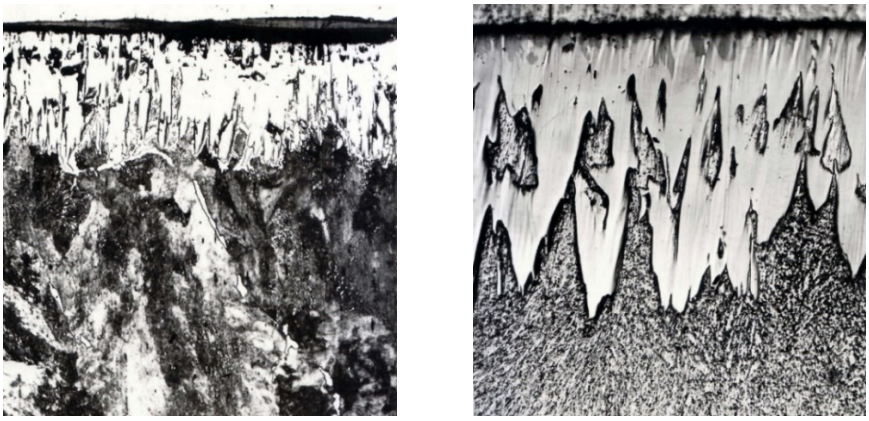
Thus, it has been experimentally shown that under conditions of fretting corrosion, the intensity of destruction of contacting metals depends on their electrochemical properties, as well as on the presence of components in the external gas environment that affect the kinetics of electrochemical processes (oxygen, moisture). It has been established that fretting corrosion of metal surfaces creates conditions conducive to electrochemical processes, which, along with other factors (e.g., fatigue phenomena), determine the mechanism and selectivity of the destruction of contacting metals. Electrochemical corrosion develops due to the accumulation in the contact zone of a highly dispersed layer of oxides saturated with adsorbed oxygen and moisture in charged forms. From the point of view of the adsorption-electrochemical mechanism of fretting corrosion, a number of known experimental facts can be explained. Thus, in some experiments [2], when the relative humidity of the environment was increased to 30-40%, an increase in the intensity of fretting corrosion of steel was initially observed, and with a further increase in humidity, the damageability of the contacting surfaces decreased. Since the adsorption activity of oxides increases with the degree of surface hydration, an increase in the concentration of adsorbed oxygen and moisture molecules in the friction zone within certain limits should be accompanied by an increase in fretting corrosion from the point of view of the adsorption-electrochemical mechanism. However, with a further increase in the concentration of adsorbed oxygen, the corrosion rate should decrease due to the passivation of steel [18]. The growth in the intensity of fretting corrosion at low temperatures is obviously associated with an increase in the adsorption activity of oxides, and the usually observed high susceptibility to fretting corrosion of surfaces with an increased purity class [1,2] is probably explained by the fact that polished surfaces are more susceptible to electrochemical corrosion. Taking into account the possible development of contact fatigue and corrosion fatigue processes under fretting conditions, the protective effect of diffusion chemical-thermal coatings was researched, which are known to contribute to an effective increase in the corrosion fatigue strength of steel. In many cases, parts subjected to chemical-thermal treatment (CTT) do not require anti-corrosion protection. The interaction of compressive stresses created by diffusion coatings with stresses from external loads leads to a significant increase in resistance to cyclic loads. The creation of a surface diffusion layer during CTT increases the critical stress of dislocation sources and inhibits the processes of shear formation and plastic flow transfer from grain to grain. When two- or multi-phase structures with sharply different plasticity are formed, materials acquire high relaxation capacity under cyclic loads [12]. We studied the fretting resistance of normalized 45 steel treated with several types of diffusion saturation during CTT, as well as, for comparison, steel in a hardened state (Table 2). Chemical-thermal treatment was carried out in appropriate reaction mixtures using standard methods. A cylindrical (fixed) sample was treated (see Fig. 1 *b*), and the indenter was a movable sample made of 45 steel, hardened and tempered.

Table 2

Effect of chemical-thermal treatment of 45 steel on fretting resistance (P = 30 MPa; A = 0,05 mm; f = 30 Hz)

No.	Type of processing	Fretting resistance, $Q \cdot 10^{-3}$ cycle/μm
1	Steel 45 (normalization)	40
2	Steel 45 hardened	65
3	Vanadium coating	70
4	Siliconization	114
5	Boronization	120
6	Chromium plating	160
7	Alitization	175
8	Boronization	185
9	Borosilication	450

The criterion for fretting resistance Q was taken to be the ratio of the number of fretting cycles to the linear wear of the friction zone at a given specific load, slip amplitude, and vibration frequency (based on $N_f = 5 \cdot 10^5$ cycles). This value shows the number of load cycles required to destroy a surface layer of a unit depth. Of the types of CTT studied, chromium plating, alitization, boronization, and borosilication showed the most significant increase in fretting resistance. The positive effect of chromium plating is due to the fact that chromium is an easily passivated element, so that such alloying of the surface layer, along with substructural hardening and the creation of residual compressive stresses, leads to the inhibition of anodic processes, increasing the corrosion resistance of steel. The high fretting resistance of the aluminized layer is due to the ability of aluminum to form a stable Al_2O_3 oxide film during oxidation, which has high protective properties and protects the metal from corrosion. However, it is necessary to saturate to a depth of no more than 0.05 mm, since a greater saturation depth (0.1-0.2 mm) leads to a decrease in the fatigue strength of steel. It is important to note the high effectiveness of boron-containing coatings in resisting fretting corrosion. Indeed, conventional boronizing increases the fretting resistance of steel more than fourfold, while borosilicating increases it tenfold. After boronizing, the modified layer consisted mainly of two types of solid borides—FeB and Fe_2B—in the form of needles directed perpendicular to the saturated surface (Fig. 8*a*).



a) ***b***)

Fig. 8. Microstructure of diffusion coatings on 45 steel (×450): *a* – boronization; *b* - borosilication

To increase the load-bearing capacity of the transition zone, the boronized samples were subjected to hardening (from 840°C) and low-temperature tempering (200°C), which formed a tempered martensite structure in the boride substrate. Borosilication forms needles of iron borides (mainly Fe_2B) elongated in the direction of diffusion of the saturating elements, and in the space between them, a phase representing a solid solution of silicon and boron in iron (Fig. 8*b*). Such a compositionally heterogeneous structure with high hardness is characterized by high damping capacity (internal friction), which, in addition to corrosion protection, provides an increase in contact fatigue strength [12].

Conclusions

Data has been obtained that expands theoretical understanding in the field of physicochemical mechanics of contact interaction during low-amplitude fretting.

The susceptibility of metals to fretting corrosion develops in accordance with the following three stages:

1. Period of adhesion-deformation strengthening of contact surfaces and cyclic flow of subsurface layers with their transition to an ultradisperse (nanocrystalline) state with high reactivity (chemical corrosion).

2. Incubation period, which is accompanied by the accumulation of fatigue damage in the subsurface layer and the formation of a reaction-active interlayer of oxides in a highly dispersed state.

3. The period of corrosion-fatigue failure of mating surfaces, when conditions favorable for the development of electrochemical corrosion are created, which, along with fatigue phenomena, determines the mechanism and selectivity of fretting wear at this stage.

Electrochemical corrosion becomes the leading process after the formation of a highly dispersed oxide layer saturated with oxygen and moisture adsorbed in reactive radical forms in the contact zone. Metal oxides, as semiconductors, have specific properties that influence the processes of adsorption and catalysis in tribochemical reactions. These data expand the scope of application of traditional methods of electrochemical protection capable of changing the nature and kinetics of tribochemical reactions under fretting conditions.

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Шевеля В.В., Олександренко В.П., Диха О.В., Соколан К.С. Трибохімія ушкодження металевих сполучень при фреттинг-корозії

Досліджувались закономірності фреттинг-зносу ряду конструкційних матеріалів та гальванічних покриттів з урахуванням їх механічних та фізико-хімічних властивостей. Проводилась оцінка впливу на інтенсивність фреттинг-зносу складу газового середовища (повітр, кисень), а також контактного навантаження з однойменною реєстрацією температури в зоні тертя. Отримано дані, що свідчать про можливість розвитку при малоамплітудному фреттингу металів у повітряному середовищі поряд з окислювальними процесами електрохімічної корозії. Розглянуто фізико-хімічні передумови ініціювання в зоні вібраційного контакту електрохімічних процесів при формуванні ультрадисперсного прошарку оксидів, які стають каталізатором прискореної хемосорбції кисню і вологи у радикальних та іон-радикальних формах. В результаті, згідно з електронною теорією адсорбції та каталізу на напівпровідниках (окислах), контактні явища починають розвиватися за механізмом автокаталітичної корозії. Після латентного періоду накопичення оксидів створюються умови для електрохімічних процесів, що сприяють корозійно-втомному руйнуванню сполучених поверхонь. Результати дослідження розширюють уявлення про природу корозійних процесів при частковому та змішаному ковзанні, орієнтуючи на можливість застосування традиційних методів електрохімічного захисту для підвищення фреттингостійкості вузлів тертя, що працюють в умовах вібрації.

Ключові слова: фреттинг-знос, коефіцієнт тертя, фреттингостійкість, адсорбція, корозія, електрохімія, хіміко-термічна обробка