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Influence of the contact geometry of tribo pair metal elements on fretting-corrosion wear

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Some issues of the dependence of the wear value of tribocouple materials on the contact geometry and dimensions of tribocouple elements, as well as on the fretting loading amplitude are considered. The research was carried out using the "plane-cylinder" contact scheme and planar annular contact of a solid or a segmented ring with the end surface of the cylinder on samples made of titanium alloys VT20, VT8, and VT22 and aluminum alloy D16T. The comparative tests in the "plane-cylinder" scheme on samples made of VT20, VT8, and D16T alloys showed an increase in wear value with an increase in the relative displacement of the surfaces. Using electron microscopic and X-ray spectral analyses, the mechanism of formation of protective secondary structures on the friction surface was studied. It was shown that the critical amplitude of fretting above which the wear value increases sharply is smaller for this type of contact; this provides better opportunities for removing wear products from the friction zone.

Keywords: contact geometry, fretting-corrosion, relative vibration displacement, protective structures, wear

Вплив геометрії контакту металевих елементів трибопари на фретинг-корозійне зношування. *М.В. Кіндрачук, О.І. Духота, В.В. Харченко, Т.С. Черепова, А.О. Корнієнко, В.Б. Мельник, А.О. Юрчук*

Розглянуті питання залежності інтенсивності зношування матеріалів пар тертя від схеми і розміру контакту елементів трибопари, а також від амплітудно-навантажувальних параметрів фретингу. Дослідження проводились за схемою контакту «площина-циліндр» та площинного кільцевого контакту суцільного і приривчастого кільця з торцевою поверхнею циліндра, на зразках із титанових сплавів ВТ20, ВТ8, ВТ22 та алюмінієвого сплаву Д16Т. Аналіз результатів порівняльних випробувань за схемою «площина-циліндр» зразків із сплавів ВТ20, ВТ8 і Д16Т показав, що зі збільшенням параметра відносного зміщення поверхонь, інтенсивність зношування зростає. За допомогою електронно-мікроскопічного та рентгеноспектрального аналізу досліджено механізм формування на поверхні тертя захисних вторинних структур. Критична амплітуда фретингу вище якої інтенсивність зношування різко зростає, буде меншою для такого типу контакту, який забезпечує кращі можливості відведення із зоні тертя продуктів зношування.

1. Introduction

To ensure a high level of reliability and durability of tribological systems, one of the most important tasks is to determine the optimal design and dimensions of contact for given friction conditions and combination of materials in a tribo-pair. Under conditions of fretting-corrosion wear, due to small amplitudes of relative displacements, surface destruction occurs in the zones of actual contact. In this case, depending on the ratio of the geometrical parameters of the contact and the amplitude of the relative displacement, wear products can be freely removed or accumulated in the friction zone. It is obvious that the nature and intensity of wear significantly depend on both the shape and size of the contact area [1-4], as well as on the crack resistance of the surface [5] and the amplitude of vibration displacement [6].

To determine the mutual influence of the mentioned factors on the intensity of fretting-corrosion, the dependence of fretting wear on the degree of relative displacement of the conjugated surfaces K_z was studied; the parameter K_z is determined by the ratio of the fretting amplitude A to the half-width of the contact area in the direction of vibration displacement: $K_z = A/l$. The importance of the K_z parameter for tribosystems subject to fretting- corrosion wear is that it affects the conditions for the release of wear products from the friction zone, the penetration of the external environment into the friction zone, and, consequently, the interaction of the frictional contact surfaces [7-10]. At the same time, it is necessary to take into account the local nature of loading [11] and the structure evolution [12].

2. Experimental / Theoretical details

The research was carried out on an IMF vibration tribometer according to the "plane-cylinder" contact scheme [13], and a modernized MFC-1 friction machine [7] according to the planar annular and "plane-cylinder" contact schemes. Titanium alloys VT20, VT8, and VT22 and aluminum alloy D16T were used as sample materials.

When testing in the "plane-cylinder" contact scheme on the IMF vibration tribometer, wear-resistant nitrided steel 30HGSNA as material for countersamples was used to minimize the impact of changes in the shape of the countersample due to wear on the experimental conditions.

The tests were carried out under the normal atmospheric conditions without lubrication. The normal load force per unit contact length was constant in all experiments and amounted to 4.1 N/mm, the amplitude of vibration displacement A=500 µm, the frequency of oscillations f = 50 Hz, and the test base $N = 0.9\cdot10^5$ cycles and $N= 1.8\cdot10^5$ cycles. Based on the results of the tests, the linear wear of the samples was determined in the zones of maximum wear along the friction track. During the experiment, a signal was recorded from the piezoelectric sensor of the system for measuring the force of resistance to the movement of the countersample, which is proportional to the friction force.

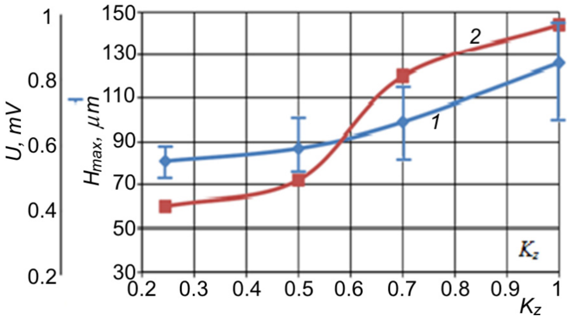


Fig. 1. Dependence of the maximum linear wear H_{max}(1) and the piezoelectric sensor signal U (2) on the parameter of the relative displacement of the surfaces of the sample and countersample K_z during the wear test under the conditions of fretting-corrosion

Test conditions on the IFC-1 friction machine according to the schemes of the planar annular and "plane-cylinder" contacts are given in the captions to Figs. 7 and 8, respectively.

3. Results and discussion

The change in the averaged values of the maximum linear wear H_{max}, their dispersion, and the values of the sensor signal U depending on the relative displacement parameter K_z are presented in Fig. 1. The following conclusions can be drawn from the analysis of these dependences:

1. At a constant fretting amplitude, the wear value will be greater, the closer the parameter K_z is to 1. Herein, the wear increases most rapidly when the K_z parameter exceeds a certain threshold value in the region of $K_z \geq 0.5...0.6$. In the same range of the K_z parameter, a sharp increase in the signal of the piezoelectric sensor is observed, which can be associated with an increase in the friction force and, accordingly, with an increase in the friction load of the surface layer material.

2. The second important conclusion is that larger values of the K_z parameter correspond to a higher spread of wear values. That is, with an increase in the relative displacement of the surfaces of the tribopair elements, the degree of stochasticity of the processes responsible for fretting-corrosion wear of the material increases as well.

According to the accepted contact scheme, when $K_z \geq 1$, in each cycle of relative displace-

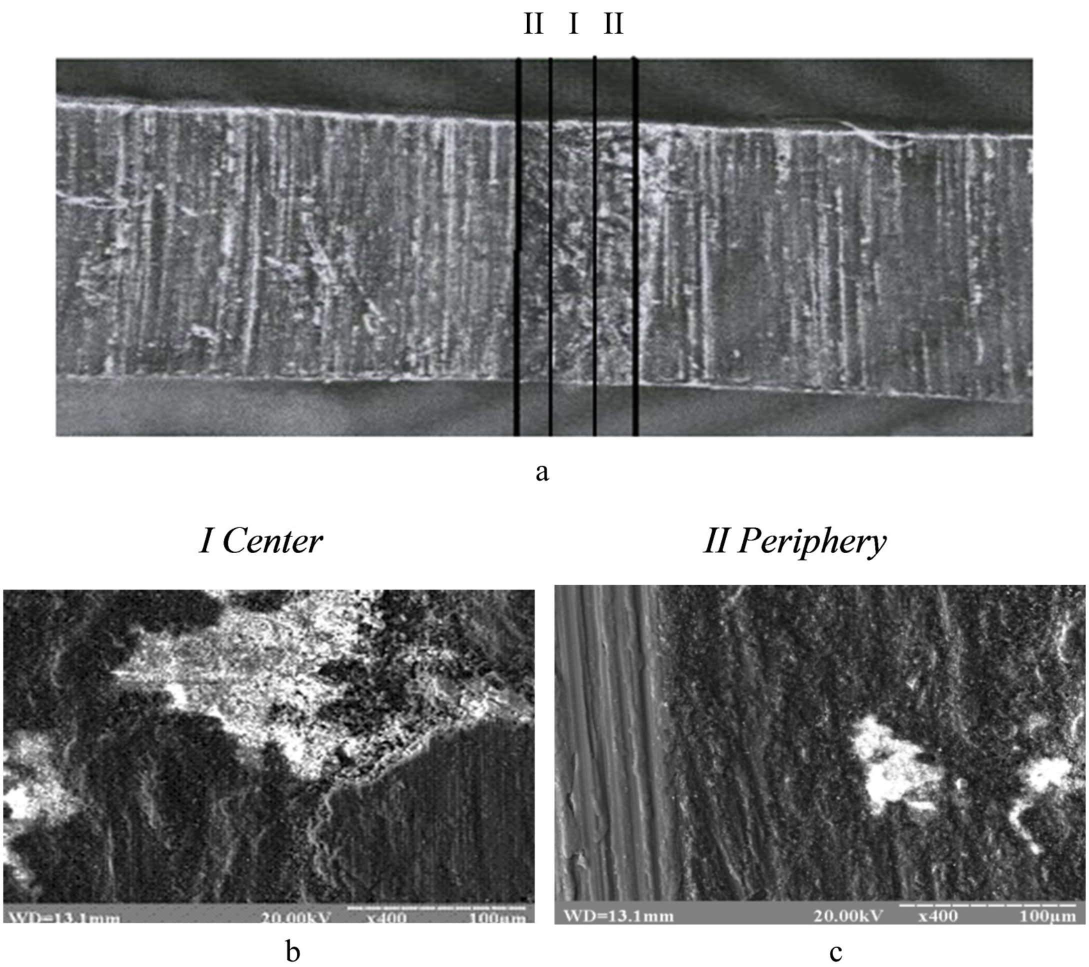


Fig. 2. General view *(a*, ×8) and electron microscopic images of the friction track surface of alloy D16T sample after fretting wear tests (*b; c* – secondary electron images)

ment, all points of the friction surface of the countersample (moving tribopair element) come out of contact with the surface of the sample (stationary tribopair element). In this case, the friction surface of the counterbody is fully open, and the most favorable conditions are created for the release of free particles of wear products from the friction zone. When each point of the friction surface of the sample is constantly in contact with the countersamle, this case is characterized by a low rate of the formation and regeneration of protective oxides and adsorbed films on the surface of the sample and their high rate on the surface of the countersample.

When K_z approaches 0, which is typical for surfaces with a large length of contact areas in the direction of vibration displacement and for small fretting amplitudes, the rate of wear products leaving the friction zone decreases. This can be considered as a change in the nature of the interaction of tribosystem elements, when the probability of frictional interaction of the tribopair elements through areas with direct metal-to-metal contact is reduced due to the formation of a more effective layer of wear products between the friction surfaces. It is obvious that under such conditions, the dynamic load of the frictional contact will decrease, and the intensity of material wear will be largely determined by the ratio of the rates of three interconnected tribological processes:

- triboactivation and tribochemical interactions of tribopair materials with active components of the environment and with each other → destruction of friction surfaces and separation of free particles of wear products → accumulation and removal of wear products from the friction zone.

The influence of each of these processes on the intensity of fretting-corrosion depends both on the tribopair materials and the geometrical parameters of the contact. Herein, the role of the latter can significantly change depending

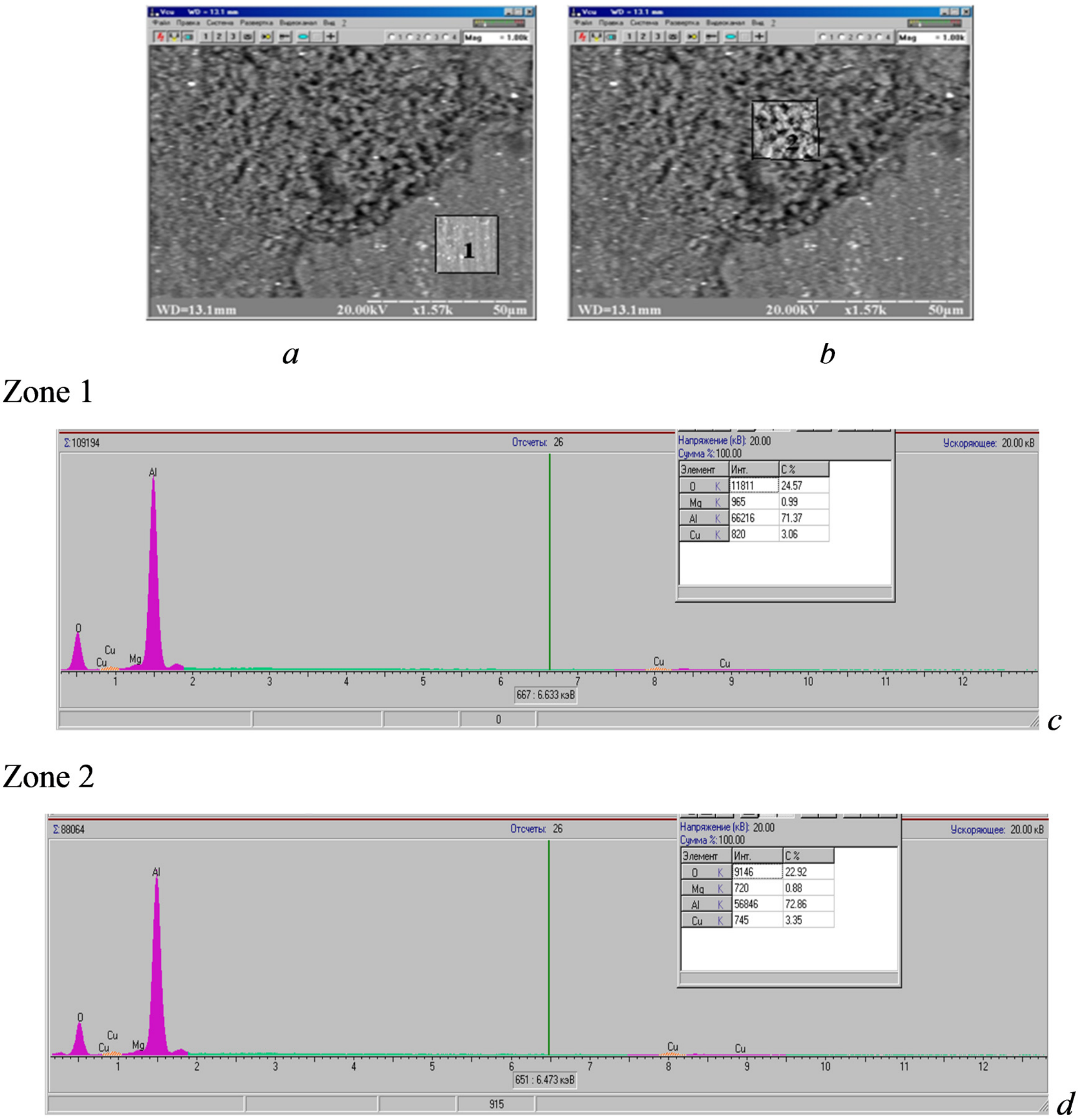


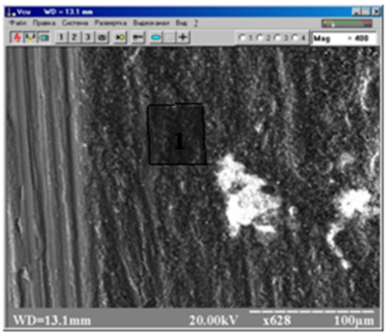
Fig. 3. Scanning zones (*a; b*) and the results of X-ray spectral analysis of the percentage distribution of chemical elements (*c; d*) on the friction surface of alloy D16T after fretting wear tests. Central area of contact

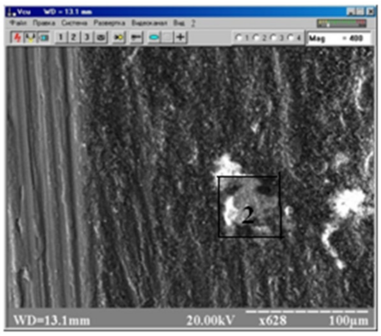
on the scheme of the initial contact and the stage of the developing fretting process.

For the "plane-plane" contact scheme, the plot of the distribution of the specific contact load under the conditions of constant normal external force at all stages of fretting (p=const) remains unchanged, and the relative displacement of the conjugated surfaces for most real tribonodes is very small ($K_z \rightarrow 0$). In this case, in the central areas of contact, the friction zone has less contact with the external environment for removing wear products from the friction zone compared to the peripheral areas. In this regard, at the first stage of fretting for the peripheral areas, the most likely reaction will be the reaction of activated surface layers of metal with oxygen, leading to the formation of passivating oxide films, and the development of wear by the corrosion-fatigue mechanism.

For the central areas, as a result of limited oxygen supply, one can expect activation of solid-phase interaction reactions and wear of tribopair materials by the adhesive wear mechanism. Gradually, due to an increase in roughness and a decrease in the surface contact density, the front of tribochemical oxidation reactions will spread from the peripheral to central areas of the contact.

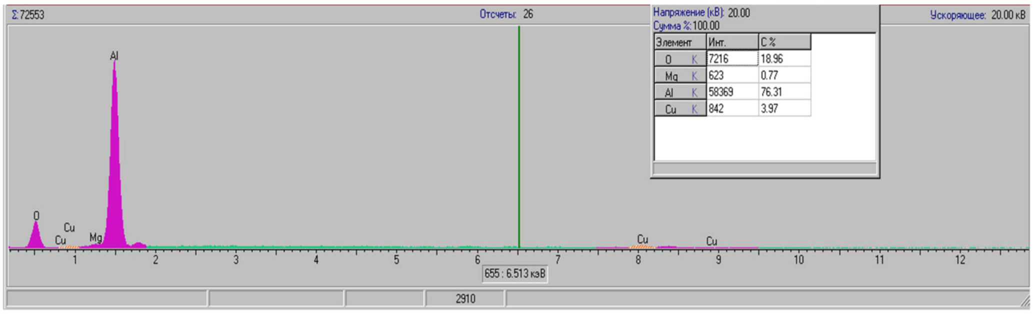
In open tribosystems, the rate of release of wear products from the friction zone is equal





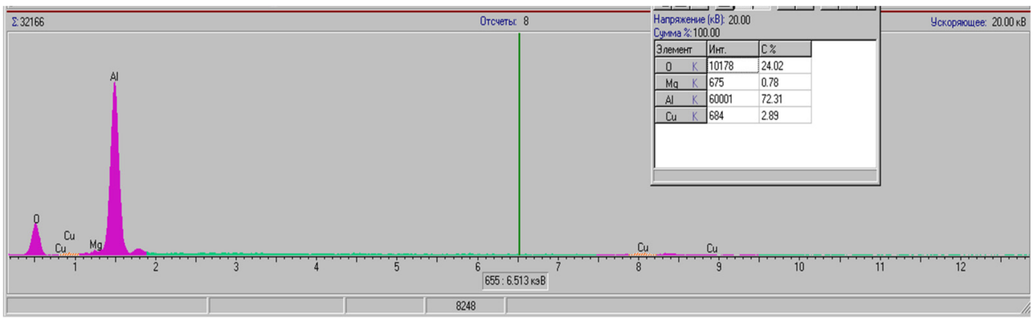
a *b*

Zone 1



c

Zone 2



d

Fig. 4. Scanning zones (*a; b*) and the results of X-ray spectral analysis of the percentage distribution of chemical elements (*c; d*) on the friction surface of alloy D16T after fretting wear tests. Peripheral area of contact

to the rate of their formation; as a result, the elements of the tribopair will interact through a layer formed by wear products. This will contribute to the deconcentration of local contact stresses in the areas of actual contact, reducing the frictional load on the friction surfaces and, accordingly, the intensity of wear.

In closed tribosystems, the rate of formation of wear products exceeds the rate of their removal from the friction zone; in this case, for materials of tribopairs with a total coefficient of material increment greater than 1, the pressure in the tribosystem will gradually increase due to the conversion of the worn volume of metal into oxides. As reported in [8], in this case, the developing fretting process may cause the loss of mobility and jamming of the connection.

In contrast to the "plane-plane" contact, in conjugates with local point and linear contacts, the wear of tribosystem elements is accompanied by an increase in the nominal contact area. At the same time, the specific contact loads acting in the conjugates decrease. At the initial stage of fretting, there is a free flow of air into

Table 1. Mechanical properties and results of comparative wear tests under fretting-corrosion of samples of titanium alloy VT8 and aluminum alloy D16T

No.	Material of sample	$\sigma_{0,2}$, MPa	σ_{-1}, MPa	Maximum linear wear H_{max}, μm *	
				K_z=0,3	K_z=0,6
1	Alloy VT8	100...120	45...50	120.0	140.0
2	Alloy D16T	45	15	105.0	135.0

*Test conditions: A = 300 μm; p = 4.1 H/mm; f = 50 Hz; $N = 1.8 \cdot 10^5$ cycles. Countersample – steel 30KhGSNA nitrided

Table 2. Results of X-ray spectral analysis of the percentage distribution of chemical elements on the friction surface of VT8 alloy after wear tests under fretting-corrosion conditions

Microareas of scanning	Content of chemical elements, mass%			
	O	Al	Ti	Mo
I. Central area				
1	15.90	6.01	75.57	2.52
2	39.10	4.60	54.40	1.91
3	45.20	4.20	49.13	1.40
II. Peripheral area				
1	13.67	4.66	79.62	2.05
2	38.92	3.40	56.16	1.52
3	34.21	3.71	60.57	1.51

the friction zone, which allows intensive reactions of tribochemical interaction of activated surface layers of metal with oxygen to occur. This period is also characterized by a relatively free release of wear products from the friction zone. Under such conditions, high specific stresses in the local contact even at low external normal force will stimulate the destruction of oxide films and the development of fretting-corrosion by the mechanism of adhesive wear.

It can be expected that with an increase in the number of fretting cycles, the nature of friction contact interaction processes in tribosystems with local point and linear contacts will increasingly acquire the features of tribosystems with a plane contact.

The established features of the influence of contact geometry on the development of fretting-corrosion wear explain the results of comparative tests on fretting resistance of two structural alloys that differ in strength and physical-chemical properties, namely titanium alloy VT8 and aluminum alloy D16T. As can be seen from Table 1, with the selected contact scheme and conditions of frictional contact interaction, despite the significantly higher volumetric static and cyclic strength of the VT8 alloy, its wear resistance is lower than that of the D16T alloy.

The higher fretting resistance of alloy D16T can be explained by the formation of a combined protective layer made from hard particles of aluminum oxide Al_2O_3 (a component of wear products) embedded in the surface of aluminum alloys in the fretting-corrosion process [7]. The presence of such structures is confirmed by the results of electron microscopic and X-ray spectral analyses (Figs. 2–4).

A lower density of the surface curved with oxide particles is observed in the peripheral areas of the contact, where the conditions for the release of wear products from the friction zone are more favorable than in the center. It is obvious that a similar effect causes a noticeable decrease in the fretting resistance of alloy D16T under test conditions at K_z=0.6.

On the friction surface of alloy VT8, structures with a similar formation mechanism are not observed, which may be related to the lower hardness ratio of the base metal to its oxides in titanium alloys compared to aluminum-based alloys.

Instead, surface structures of black and gray color are recorded on the friction track of alloy VT8 samples (Fig. 5). Based on the content of the main chemical elements and oxygen (Table 2), they can be identified as phases at different stages of titanium oxidation.

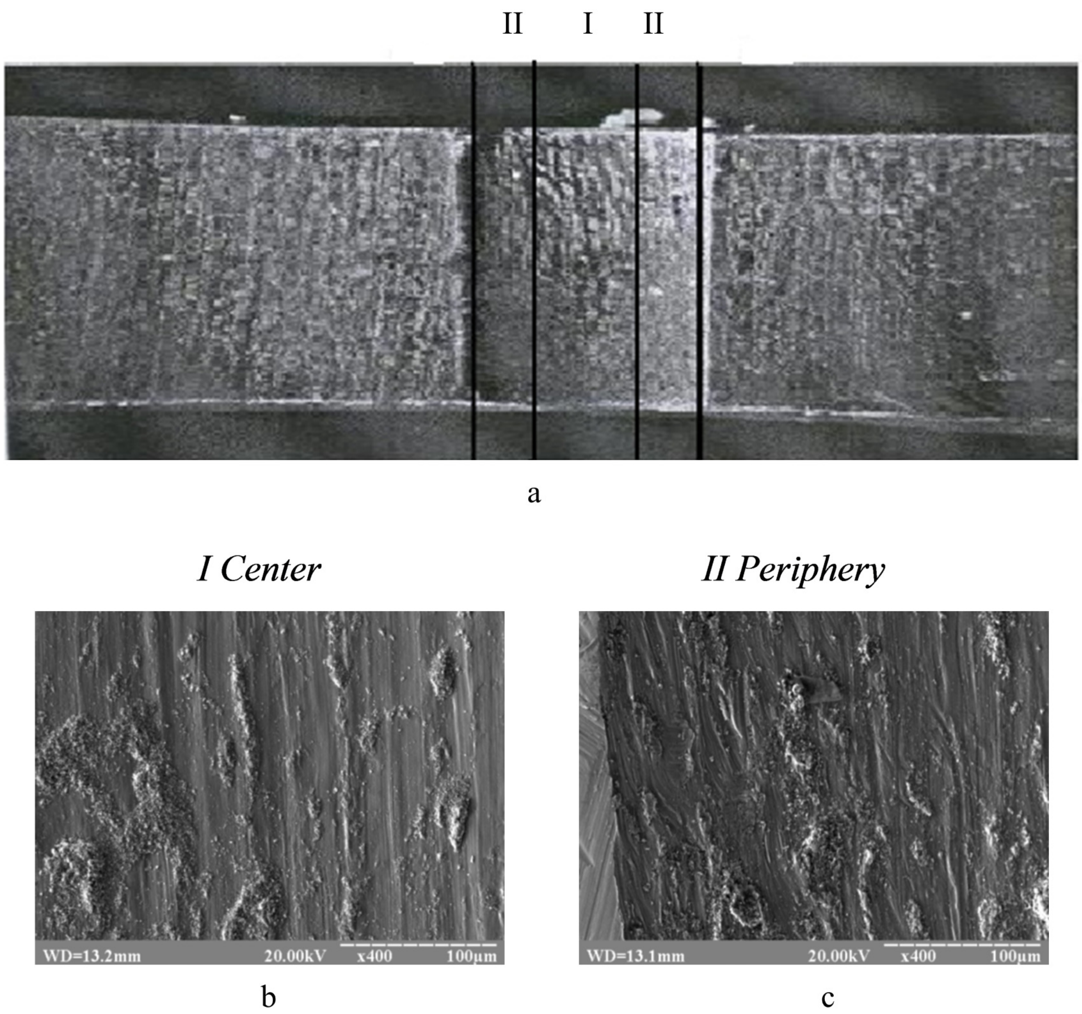


Fig. 5. General view (a, ×8) and electron microscopic images of the friction track surface of alloy VT8 sample after wear tests under fretting-corrosion conditions: b – secondary electron image; c – reflected electron image

The relatively small specific area of such structures both in the central and peripheral zones of contact indicates their low adhesive and cohesive strength [14, 15]. In this case, the main protective role is played by the intermediate layer formed from free particles of wear products between the friction surfaces. Naturally, the effectiveness of the protective effect of this layer will be lower at higher K_z values. Probably, for this reason, the intensity of wear of VT8 alloy increases with increasing parameter of the relative displacement of the surfaces (Table 1).

To determine the influence of the contact geometry on the dependence of the value of wear on the fretting amplitude, studies were carried out using three variants of contact schemes for tribocouple elements: plane contact of the continuous ring end of the moving cylindrical countersample on the end of the cylindrical stationary sample; intermittent contact of an annular segmented movable cylindrical countersample on the end face of the cylindrical stationary sample; contact of the flat surface of the stationary sample with the initial cylindrical surface of the moving countersample. The schemes of the initial contact, test conditions, and experimental results are presented in Figs. 7 and 8.

From the analysis of the dependences obtained, it can be concluded that the critical fretting amplitude above which the intensity of wear increases sharply will be smaller for the type of contact, which provides better opportunities for the removal of wear products from the friction zone. Under this condition, the location of the transition region from small to large values of fretting wear will be determined by the parameters of the contact geometry and the amplitude-load parameters of fretting; their

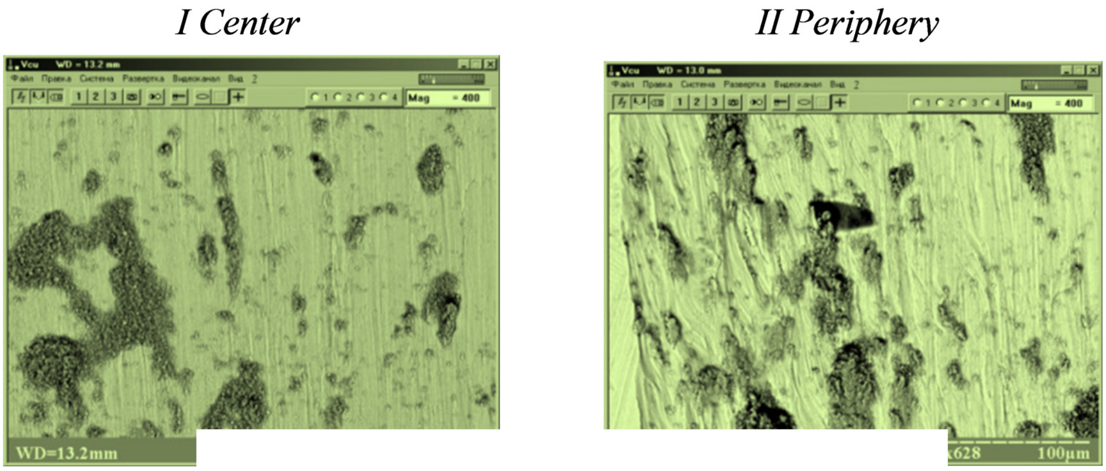


Fig. 6. Micro-areas scanned by X-ray spectral analysis of the friction surface of alloy VT8 after wear tests under fretting-corrosion conditions

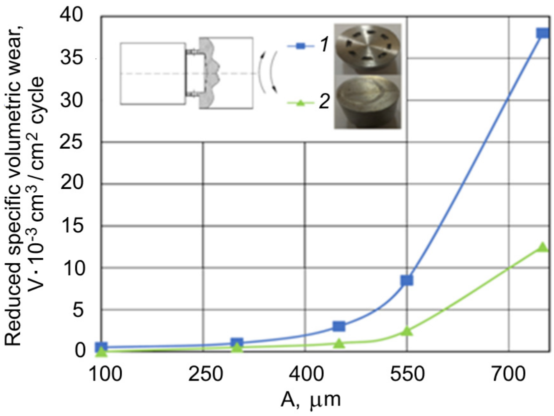


Fig. 7. Dependence of the reduced specific volumetric wear of alloy VT8 on the fretting amplitude: 1 – segmented annular contact; 2 – planar solid ring contact. Test conditions: P = 19.6 MPa; V = 30 Hz; 1 – N = $5{\cdot}10^4$ cycles; *2* – N =$5{\cdot}10^5$ cycles; T = 293 K. Tribopairs of the same name

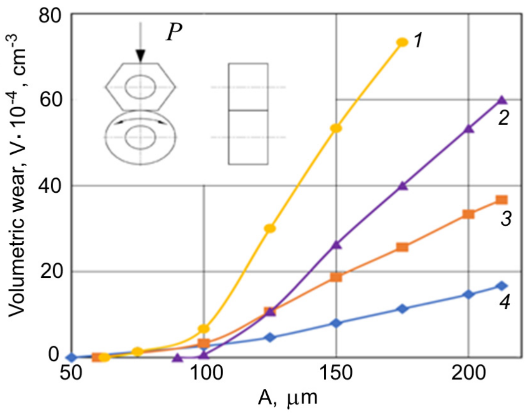


Fig. 8. Volumetric wear value of VT22alloy depending on the fretting amplitude. Initial contact: "plane-cylinder". Test conditions: 1 – P=130 N/mm; 2 – P = 65.8 N/mm; 3 – P = 13 N/mm; 4 – P = 6.5 N/mm; V = 30 Hz; T = 293 K. The material of the countersample is ShKh15 steel

combined influence on the physicochemical processes determines the formation of physical contact between the elements of the tribo-pair and its transition from frictional interaction primarily through a layer of wear products to direct frictional interaction of materials in the tribo-pair.

4. Conclusions

According to the results of wear tests under fretting-corrosion conditions, a dependence was obtained that shows that with an increase in the relative displacement parameter of the surfaces of the tribopair elements, the fretting-corrosion wear of the surface layer increases; the highest rate of wear is observed when the relative displacement exceeds a certain average value of K_z ≥0.5...0.6 for the selected contact scheme and fretting conditions. The effect of the contact scheme of the tribopair elements on the dependence of the fretting wear value on the fretting amplitude was determined. The critical amplitude of fretting, above which the intensity of wear increases sharply, was shown to be smaller for the type of contact that provides better opportunities for the removal of wear products from the friction zone.

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