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Methodology for Selecting Compatible Metal Materials for Friction Pairs During Fretting-Corrosion Wear

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Taking into account the various forms of fretting-corrosion manifestation, on the example of the contact of titanium alloy BT8 with structural alloys based on Al, Cu, Mg and Fe and with the same material, an attempt is made to develop a complex approach to the selection of compatible materials of friction pairs. According to the research results, the quantitative indicators of fretting wear of friction-pair materials are defined, and the regularities of mutual influence of the nature and properties of the materials on the friction-wear parameters of the tribosystem are analysed. For tribosystems, where the loss of functionality is associated with the accumulation of wear products, a calculation method for determining the compatibility of materials based on the volume-increment coefficient of the materials within the tribocontact zone is proposed.

Key words: tribomechanical system, friction pairs, fretting corrosion, wear resistance, wear products.

З урахуванням різних форм прояву фреттинґ-корозії, на прикладі контакту титанового стопу ВТ8 із конструкційними стопами на основі Al, Cu, Mg, Fe та в однойменній парі здійснено спробу комплексного підходу щодо вибору сумісних матеріялів пар тертя. За результатами досліджень визначено кількісні показники фреттинґ-зношування матеріялів пар тертя, проаналізовано закономірності взаємного впливу природи та властивостей матеріялів на фрикційно-зношувальні параметри трибосистеми. Для

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трибосистем, в яких втрата працездатности пов'язана з накопиченням продуктів зношування, запропоновано розрахунковий метод визначення сумісности матеріялів за коефіцієнтом прирощення об'єму матеріялу в зоні трибоконтакту.

Ключові слова: трибомеханічна система, пари тертя, фреттинґ-корозія, зносостійкість, продукти зношування.

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1. INTRODUCTION

Taking into account the general tendency to decreasing material consumption, reducing structural stiffness, increasing workloads and requirements for the economic efficiency of using machines, the issues of increasing their reliability and durability are becoming extremely important. In solving them, one of the key places belongs to ensuring a high level of wear resistance and the duration of the period of trouble-free operation of parts and components of tribomechanical systems. In aircraft structures, as well as in the structures of other dynamically loaded machines, among the tribomechanical systems with the most limited durability, there are tribosystems of low-motion and nominally immobile nodes and joints, the parts of which are damaged by fretting corrosion.

In engineering practice and tribological studies, fretting corrosion is considered one of the most destructive, unpredictable and dangerous types of wear [1–3]. Moreover, the negative consequences of the development of fretting corrosion can be caused by not only physical wear of parts but also the wedging effect of wear products, which due to small amplitudes of mutual movements remain mainly in the contact area. It is obvious that, under such conditions, the selection of materials for friction pairs should be based on a comprehensive assessment of their compatibility, taking into account the characteristics of the change in the tribosystem state for each of the specified forms of fretting corrosion. An attempt to implement such an approach on the example of choosing a favourable combination of materials in a friction pair with titanium alloy ВТ8 was the task of this study.

2. EXPERIMENTAL/THEORETICAL DETAILS

To solve this problem, comparative wear tests were carried out under fretting-corrosion conditions, when combining the ВТ8 alloy in a pair of the same material and with bronze БрАЖ9-4, steel Х18Н10Т, hardened steel 45, aluminium alloy Д16Т and magnesium alloy МЛ5 is performed. The materials selected for the study were alloys based on different metals, had different chemical and physical-mechanical properties and different properties of their oxides. In general, such a selection of friction pair materials made it possible to analyse the relationship of the fretting resistance parameters of the tribosystem with both the properties of the friction pair materials themselves and the properties of their wear products.

The tests were carried out on the МФК-1 installation [2] in accordance with ГОСТ 23.211-80 in air at room temperature with the following fretting parameters: specific normal load of samples $P = 19.6$ MPa, relative displacement amplitude $A = 125$ µm, oscillation frequency $f = 25–30$ Hz and test base $N = 5\cdot10^5$ cycles. In each friction pair, samples of the ВТ8 alloy were immobile, and counter-bodies from the abovementioned materials were movable. After the test, the average linear wear of the samples and the mass loss of the counter-bodies were determined, according to which and the contact area and the material specific mass data, their total volumetric wears were calculated. At the same time, during the test, the moment of friction was recorded, the coefficients of friction were determined, and the topography of the surface of the friction tracks and the distribution of chemical elements on them were studied using an SEM microanalyzer РЭМ-200.

3. RESULTS AND DISCUSSION

The obtained values of the volumetric wear of the samples, counter-bodies and the total volumetric wear of the materials of the friction pairs are compared in Fig. 1. As seen, under the studied fretting conditions, the least intense wear of the ВТ8 alloy occurs during friction in pairs with the magnesium alloy and bronze. At the same time, the magnesium alloy paired with the titanium one wears out much more intensely than bronze.

Electron microscopy studies of the friction track surface in the ВТ8–БрАЖ9-4 pair revealed signs of seizure with the bronze material transfer to the titanium alloy surface (Figs. 2, 3).

Based on the analysis of the change in the friction coefficient of this pair (Fig. 4, curve *2*), we can conclude that the process of intense seizure, which is characterized by a high friction coefficient, develops in the period from $10\cdot10^3$ to $70\cdot10^3$ fretting cycles. Herein, the destruction of the seizure centres is not accompanied by deep damage, which indicates a small depth of spread of deformation hardening of bronze under the action of cyclic contact loads in the actual contact areas. The relatively small wear of the materials of this pair can be due to the formation of a specific protective layer on the friction surfaces of compressed highly dispersed wear products, in the composition of which, in view of much greater volumetric wear of bronze, relatively soft copper oxides may dominate. The formation of such protective structures, firstly, will prevent the further development of adhesion, and, second-

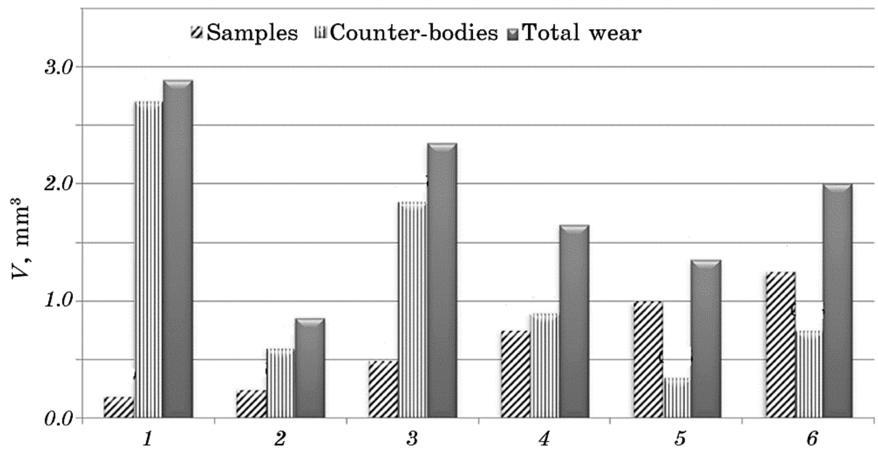
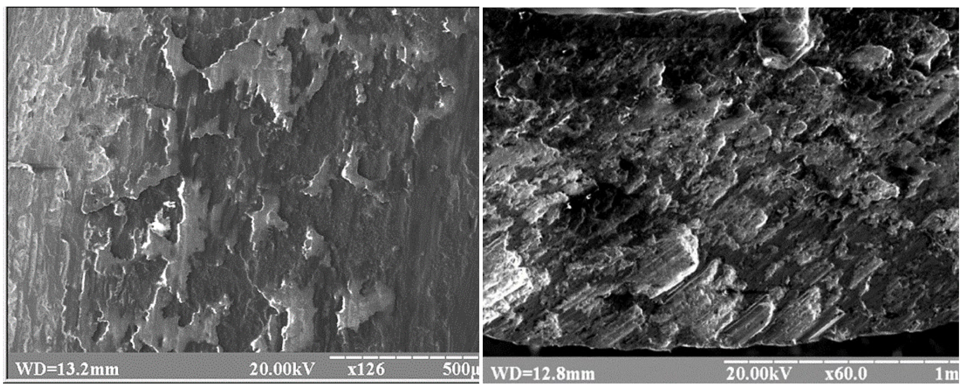


Fig. 1. Diagram of volumetric wear of samples, counter-bodies and total wear of metals of friction pairs during the wear test under fretting-corrosion conditions. Friction pairs (sample–counter-body): *1*—ВТ8–МЛ5, *2*—ВТ8–БрАЖ9-4, *3*—ВТ8–Д16Т, *4*—ВТ8–ВТ8, *5*—ВТ8–steel Х18Н10Т, *6*—ВТ8–steel 45.

ly, it reduces the intensity of destruction of contact surfaces by the mechanisms of corrosion-fatigue and abrasive wear.

In the friction pair ВТ8–МЛ5, there are no characteristic signs of intense adhesion. After 10^3–15^3 cycles of fretting, the friction coefficient decreases sharply and quickly acquires a stable and relatively low value (Fig. 4, curve *1*).

The results of the electron microscopy study of the friction track



a *b*

Fig. 2. Surface topography of the friction tracks on the ВТ8 alloy sample (*a*) and БрАЖ9-4 counter-body (*b*) after wear tests under fretting-corrosion conditions.

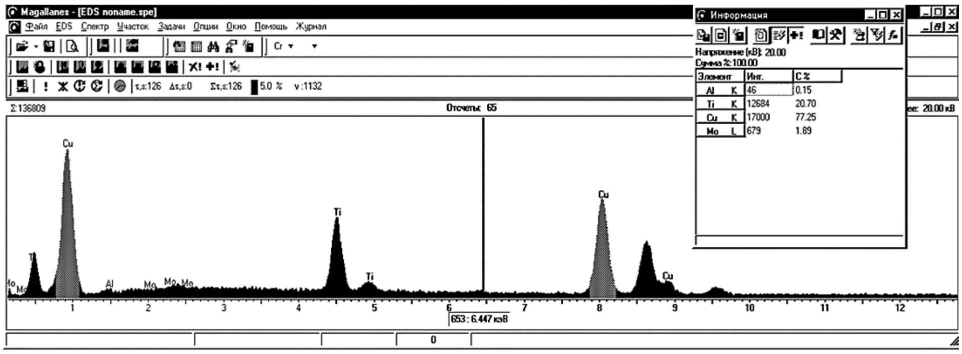


Fig. 3. Results of the analysis of the percentage content of chemical elements on the microsection of friction surface of the ВТ8 alloy paired with bronze БрАЖ9-4 after wear tests under fretting-corrosion conditions.

surface evidence that, similar to the friction in the pair with bronze, the ВТ8 friction in the pair with the magnesium alloy is accompanied by the formation of specific thin-film protective structures from compressed wear products on its surface, the composition of which includes mainly magnesium monoxide (Fig. 5, *a*, Fig. 6). On the friction surface of the magnesium alloy, characteristic signs of pitting corrosion-fatigue and grooved abrasive wear are revealed (Fig. 5, *b*).

The low disposition of materials of the ВТ8–МЛ5 pair to seizure can be explained by the fact that the mutual solubility of metals in the Ti–Mg system is practically absent [5]. According to ideas about the diffusion nature of seizure [1, 6, 7], the lack of mutual solubility and the ability of metals to form solid solutions is considered one of the main factors that prevents the formation of strong metal bonds in a friction

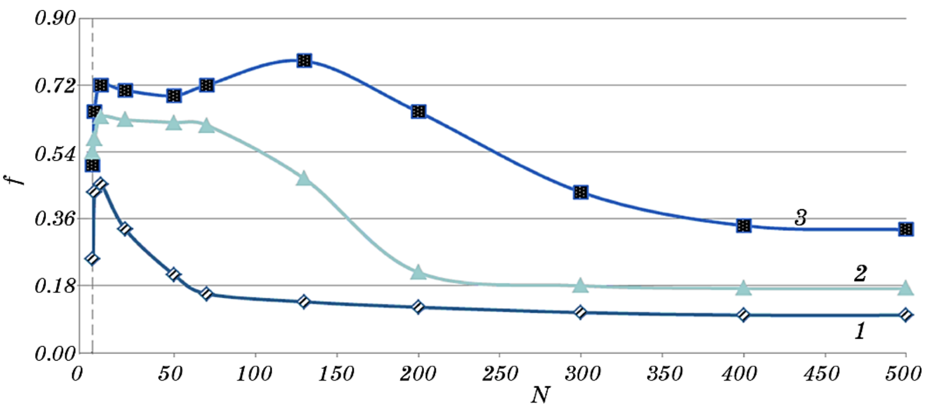
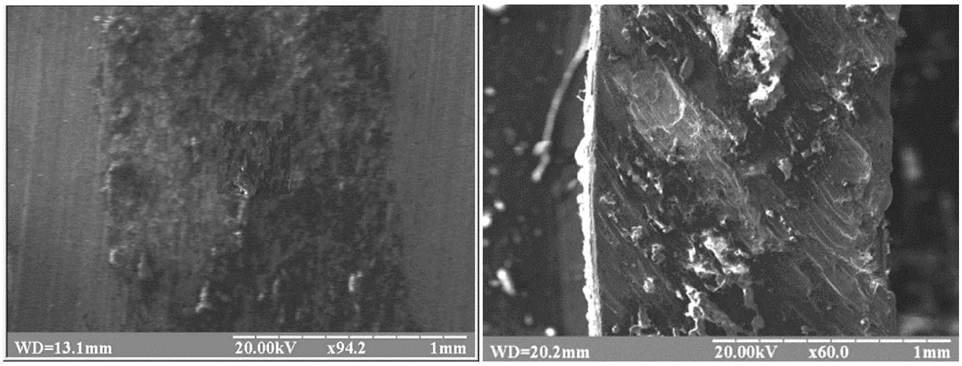


Fig. 4. Dependence of the friction coefficient on the number of fretting cycles. Friction pairs: *1*—ВТ8–МЛ5, *2*—ВТ8–БрАЖ9-4, *3*—ВТ8–Д16Т.



a *b*

Fig. 5. Surface topography of the friction tracks of the sample from BT8 alloy (*a*) and counter-body from МЛ5 alloy (*b*) after wear tests under fretting-corrosion conditions.

pair and prevents adhesion. In addition, the presence of few slide systems (planes) in the magnesium crystal lattice prevents the formation of active dislocation centres with a high concentration of point defects in the places of actual contact and the creation due to plastic deformation of a crystallographic arrangement of shear planes, which is favourable for seizure. Given the leading role in the development of fretting corrosion in corrosion-fatigue and abrasive processes, the abnormally low fretting resistance of the magnesium alloy compared to the other studied alloys can be explained by its low mechanical strength and low corrosion resistance.

Taking into account the essential role of electrochemical processes in the development of fretting corrosion [2, 8], the electrochemically high corrosion activity of magnesium and its alloys can be a significant

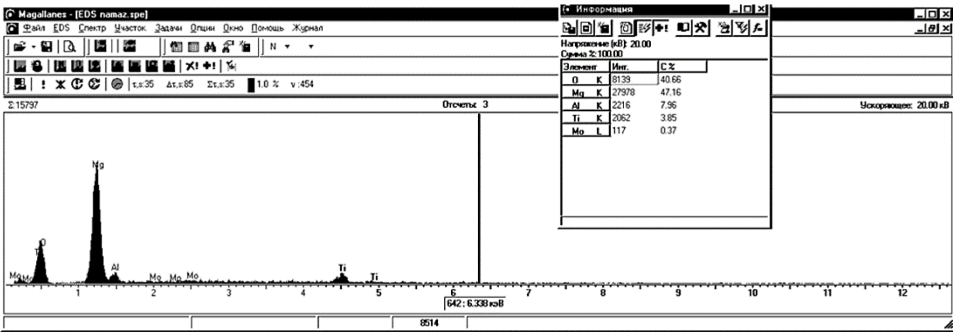


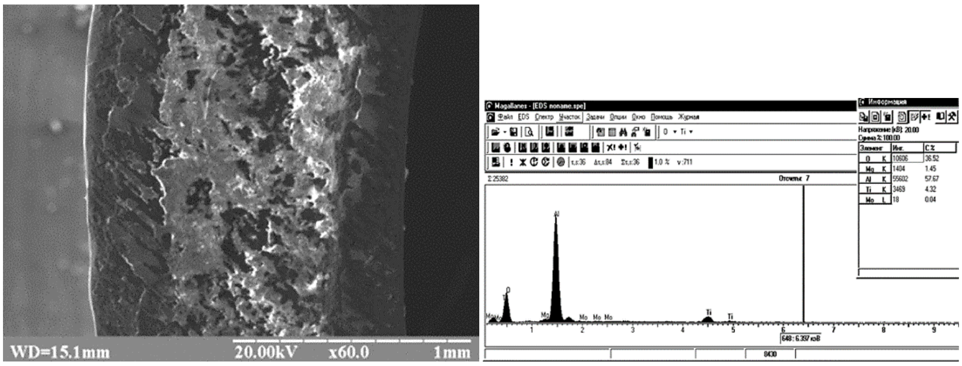
Fig. 6. Results of the analysis of the percentage content of chemical elements on the friction surface microsection of BT8 alloy paired with magnesium alloy МЛ5 after wear tests under fretting-corrosion conditions.

factor determining the high wear intensity of the magnesium alloy and the low wear intensity of the titanium alloy in the ВТ8–МЛ5 pair.

In the ВТ8–Д16Т friction pair, the development of fretting corrosion is characterized by strongly pronounced signs of seizure. The relatively long duration of the period of intense adhesion and the high friction coefficient corresponding to this period (Fig. 4, curve *3*) indicate a high strength of adhesive friction bonds. Adhesion is obviously facilitated by the low hardness of the aluminium alloy, high ability of the metals of this pair to form juvenile surfaces and the ability of titanium to form solid solutions with aluminium. As a result of the occurrence and destruction of seizure centres, deep local damage was revealed on the surface of the aluminium alloy (Fig. 7, *a*), whereas on the surface of the titanium alloy, there were areas formed from separated and transferred metal from the counter-body (Fig. 7, *b*).

Simultaneously, the friction surfaces of both the Д16Т and ВТ8 alloys, lying outside the seizure centres, undergo corrosion-fatigue and abrasive wears. Herein, the wear of the titanium alloy is higher than in the pairs with magnesium alloy МЛ5 and bronze БрАЖ9-4, whereas the main contribution to the total wear of the ВТ8–Д16Т pair is made by the aluminium alloy.

The deep destruction of the Д16Т alloy in a pair with the ВТ8 alloy can be attributing to its lower fatigue strength and tendency to strain hardening. Since the cyclic contact stresses acting in the contact zone decrease, the volumes of metal close to the plane of the welding bridges experience the greatest hardening. Accordingly, the destruction occurs in places further away from the surface where cyclic stresses exceed the fatigue strength of the material [9].



a *b*

Fig. 7. Topography of the surface of the Д16Т counter-body friction track (*a*) and the results of analysis of the percentage distribution of chemical elements in the ВТ8 sample microsection (*b*) after wear tests under fretting-corrosion conditions.

In the friction pairs BT8–steel X18H10T and BT8–steel 45, the titanium alloy wears more intensely. Herein, the amount of wear of the BT8 alloy is greater than in the pair with the same material, whereas in the pair with the BT8 alloy, the relatively soft low-strength steel X18H10T wears less than hardened steel 45.

When analysing the friction tracks of samples and counter-bodies in friction pairs BT8–BT8, BT8–steel X18H10T and BT8–steel 45, the identity of the nature of destruction of their surfaces is revealed, which corresponds to the signs of mainly corrosion-fatigue and abrasive wears. Obviously, under such conditions, the fretting resistance of friction pair materials is determined by the competition of such factors as hardness, cyclic strength and corrosion resistance. In this case, the lower fretting resistance of the BT8 alloy paired with steels can be explained by the high susceptibility of titanium and its alloys to the chemical interaction with oxygen, low strength of secondary oxide films and the tendency to flood in the fretting-corrosion process [10], whereas the higher fretting resistance in the same-named pair—by a less intense development of electrochemical corrosion processes. Given that in the process of fretting corrosion, as a result of deformation and tribochemical reactions, the surface layers of the metal undergo significant changes both at the structural and substructural levels [2, 8, 11, 12], then, the corrosion activity of the titanium alloy in galvanic pairs will be determined by its values acquired under the action of fretting rather than by the initial value of its standard electrode potential.

The results presented above make it possible to establish a favourable combination of materials in a friction pair in view of their mutual influence on frictional wear characteristics. This approach may be valid for a tribosystem, where the specified tension is lost due to wear of parts (joints with guaranteed tension), or the performance of the tribosystem is impaired by an increase in the clearance between the parts (joint with guaranteed clearance). Such tribosystems include relatively open tribosystems, where the volume of wear products formed in the contact zone (V^{I}) can be compensated by the total volumetric wear of tribocouple materials (V^{II}) and the volume of wear products removed from the contact zone (V^{III}):

$$V^{\mathrm{I}} \le V^{\mathrm{II}} + V^{\mathrm{III}}. \tag{1}$$

In closed tribosystems, where the wear products do not have a free exit from the contact zone and relation (1) is not valid, the accumulation of wear products can cause an additional increase in the specific pressure coupling. The consequence of the development of fretting corrosion in such tribosystems is most often the loss of joint mobility (jamming) and premature fatigue failure of the part [13–15]. In this case, the criterion of assessment when choosing friction pair materials can be the volume increment coefficient of the material:

$$\Delta = KV^{\mathrm{I}}/V^{\mathrm{II}}, \quad (2)$$

where K is a coefficient that takes into account the packing density of powdered wear products.

Given that the products of fretting corrosion of metal alloys are, as a rule, oxides of the base metal, the volume of wear products formed by each element of the tribosystem can be determined by the relation

$$V^{\mathrm{I}}_{\mathrm{M}i} = V^{\mathrm{II}}_{\mathrm{M}i} P, \quad (3)$$

where $V^{\mathrm{II}}_{\mathrm{M}i}$ is the volumetric wear of the i-th element of the tribosystem, P is the Pilling–Bedworth coefficient, which characterizes the ratio of the volume of the oxide formed during oxidation to the corresponding volume of the metal [16].

Considering a closed tribosystem as a closed volume where wear products undergo pressure with simultaneous application of vibration, by analogy with the vibration pressing of powder materials [17], the physical value of the coefficient K in Eq. (2) may be defined as the ability of the powdered wear products to be compacted under vibration pressing.

The volume of the powder green body changes under pressure due to the displacement of individual powder particles, which, thus, achieve a denser arrangement, as well as due to the deformation of the powder mass particles. The ability of powder materials to be compacted is determined by such physical characteristics as the granulometric composition, the size and shape of the powder particles and the ability of the powder material to undergo plastic deformation. Compaction under pressing of powder materials can be determined from the pressing equation:

$$\gamma = \gamma_g - \frac{K_0}{\alpha} e^{-\alpha p}, \quad (4)$$

where γ is the density of the compacted powdered mass, γ_g is the conditional ultimate density of the material under sufficiently high pressure, p is the applied pressure, K_0 is the initial pressing coefficient at $p = 0$, α is the coefficient of loss of compressibility, which characterizes correlation the decrease in the compression coefficient K with increasing the pressure by one unit. The constants in Eq. (4) are characteristics of powder materials and can be determined experimentally.

For brittle low-plastic powder materials, such as powders of titanium boride and titanium carbide, the density of compacts during vibration pressing, even at relatively low pressures and a short duration of vibration, can increase by 1.4–1.5 times [17].

Since at normal temperatures, metal oxides are brittle and low-plastic as well [16], due to repeated grinding in the contact zone, they acquire approximately the same shape and size, the coefficient K in equation (2) can be determined as the reciprocal of the coefficient of increase in the density of green bodies during vibration pressing and, with some approximation, be taken equal to $K = 1/1.5 = 0.66$.

Based on the above analytical study of volume changes occurring in closed tribosystems during the development of fretting corrosion, the calculation of the volume increment coefficient of the material was made. The initial data for the calculations and the obtained coefficient values are given in Table 1. The coefficient Δ is a characteristic of a tribosystem that shows how many times the volume of wear products formed during fretting corrosion becomes larger or smaller than the volume of the worn materials of the friction pair. It is obvious that under the condition of minimizing the coupling pressure and simultaneously preserving the parameters of the previously applied tension, the value of the coefficient Δ is to be ideally close to 1. As seen from Table 1, the most favourable in this case are combinations of titanium alloy ВТ8 with aluminium alloy Д16Т, bronze БрАЖ9-4 and the same alloy. In pairs with steel Х18Н10Т and hardened steel 45, despite their relatively higher wear resistances, due to the high Pilling–Bedworth coefficient of iron oxides, a significant increase in pressure is possible. A particular intense increase in pressure can be expected at the early stage of fretting corrosion, when oxide γ-Fe_2O_3 with the highest Peeling–Bedworth coefficient among the iron oxides can be predominantly formed in the wear products.

In the friction pair of the ВТ8 alloy with the МЛ5 magnesium alloy, due to the low Pilling–Bedworth coefficient of magnesium oxide and the high wear intensity of the magnesium alloy, the calculated value of the volume increment coefficient is significantly less than 1. In this case, the loss of tribosystem functionality may be due to intensely reducing the tension and increasing the clearance rather than to increasing pressure in the coupling.

4. CONCLUSION

Taking into account the peculiarities of the change in the tribosystem state under different forms of fretting corrosion, the compatibility of some structural alloys for the combination in a friction pair with titanium alloy ВТ8 was determined. It was established that to prevent deep destruction from seizure and minimize wear of the friction pair, the combination of ВТ8 alloy with БрАЖ9-4 is most favourable, and the least favourable is to make a pair with aluminium alloy Д16Т. When choosing materials for the friction pair titanium alloy–steel, preference should be given to less hard stainless steels rather than highly

TABLE 1. Initial data for calculation and calculated values of the volume increment coefficient for friction pair materials studied.

No.	Friction pairs	Friction pair sample–counterbody	Volumetric wear of pair materials $V^{\text{II}}_{\text{M}i}$, mm^3	Oxide phases in wear product	Pilling–Bedworth coefficient P	Total volume of wear products from friction pair materials V^{I}, mm^3	Volume increment coefficient of material Δ
1	ВТ8–МЛ5	ВТ8	0.19	TiO_2	1.76	2.52	0.57
		МЛ5	2.7	MgO	0.81		
2	ВТ8–БрАЖ9-4	ВТ8	0.25	TiO_2	1.76	1.48	1.15
		БрАЖ9-4	0.6	CuO	1.74		
3	ВТ8–Д16Т	ВТ8	0.5	TiO_2	1.76	3.25	0.91
		Д16Т	1.85	α-Al_2O_3	1.28		
				γ-Al_2O_3	1.45	3.56	1.0
4	ВТ8–ВТ8	ВТ8	0.75	TiO_2	1.76	2.81	1.16
		ВТ8	0.85	TiO_2	1.76		
5	ВТ8–Х18Н10Т	ВТ8	1	TiO_2	1.76	2.5	1.22
		Х18Н10Т	0.35	Fe_3O_4 magnetite	2.10		
				Fe_2O_3 haematite	2.14	2.51	1.23
				γ-Fe_2O_3	2.45	2.62	1.28
6	ВТ8–steel 45 hardened	ВТ8	1.25	TiO_2	1.76	3.77	1.25
		steel 45 hardened	0.75	Fe_3O_4 magnetite	2.10		
				Fe_2O_3 haematite	2.14	3.81	1.26
				γ-Fe_2O_3	2.45	4.04	1.33

hardened non-corrosive steels.

For tribosystems, the efficiency loss of which is associated with the accumulation of wear products in the contact zone, the determination of a favourable combination of materials in the friction pair should be performed taking into account the material volume-increment coefficient as proposed in this work. It was established that the most optimal in terms of such coefficients are combinations of titanium alloy in a pair with bronze, alloy Д16Т and the same alloy.

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