УДК 620.178.16 DOI: 10.18372/0370-2197.3(108).20445

A. KHIMKO[1], O. MIKOSYANCHYK[1], M. KHIMKO[2], O. FILONENKO[1]

[1]State University "Kyiv Aviation Institute", Ukraine
[2]Air Company LLC "H3Operations", Ukraine

WEAR RESISTANCE OF CONTACT OF TITANIUM ALLOYS WITH COMPOSITE MATERIALS DEPENDING ON THE TECHNOLOGY OF THEIR MANUFACTURING UNDER CONDITIONS OF NOMINALLY FIXED CONTACT

Titanium alloys as well as composite materials (carbon fiber and fiberglass) have recently been widely used in modern aircraft. Contact of titanium materials with polymer power composite materials under vibration loading conditions is accompanied by damage to both titanium and composite materials. The paper presents the effect on the wear resistance of contacting materials depending on the method of their manufacture and the composition of the composite material. It was determined that the wear resistance of fiberglass is 1.7-1.8 times lower than that of carbon fiber. It was determined that the total wear resistance of the Ti-CFRP contact increased by 10 % when forming the fabric in different directions compared to unidirectional forming. It was also determined that the wear resistance of the Ti5Al5V5Mo1Cr1Fe alloy increased by up to 20 % compared to the Ti6Al4V alloy when tested with composite materials.

Key words: *titanium alloys, conditionally fixed contact, wear, carbon fiber CFRP, fiberglass GFRP, damage, analysis, fretting resistance.*

Introduction. Titanium alloys, along with high-strength structural composite materials, are widely used in modern aircraft. The contact of titanium alloys with composite materials is increasingly common in aircraft and aircraft engines. Under vibration conditions, nominally fixed joints will certainly be damaged, which affects the durability of parts and their resource. Especially given the low anti-friction properties of titanium alloys and the strength properties of reinforced fibers of composite materials.

Given that the technology for manufacturing aircraft power parts from composite materials has some differences, there is a need to compare the wear resistance of titanium alloys depending on the technology for manufacturing parts from composite materials.

There are many methods for manufacturing parts from composite materials [1], which can be divided into several categories, depending on their type, desired shape and required properties of the finished product. The main methods include: contact molding, winding, vacuum diffusion, pultrusion, molding from prepregs and premixes, pressing, autoclave molding, magnetic pulse molding, injection molding, etc. For the manufacture of parts in the aviation industry, certain methods are used, which can be divided into 2 groups:

1. For the manufacture of aircraft structural elements, where the formation of fibers should be in the direction of application of the main forces during the operation of aircraft. Such methods include: winding and pultrusion. A feature of the methods is the formation of 70-90% of the fibers in one main direction of application of forces (Fig. 1a). Most of the fibers perceive the main operational load, which allows you to obtain strong and light structural elements. For example, a spar and an aircraft wing

panel where the main type of load is tension and compression in the longitudinal direction.

2. Manufacturing of aircraft power structures that are capable of taking loads in different (50/50) or approximately equal (60/40) directions. Such methods in aviation include: autoclave molding, molding from prepregs and premixes, contact molding. The fibers of composite materials are arranged randomly in different directions or predominantly in different directions, and the structure in such materials is equilateral (Fig. 1b). For example, fuselage skin, hatches and panels of the aircraft power frame [2, 3].

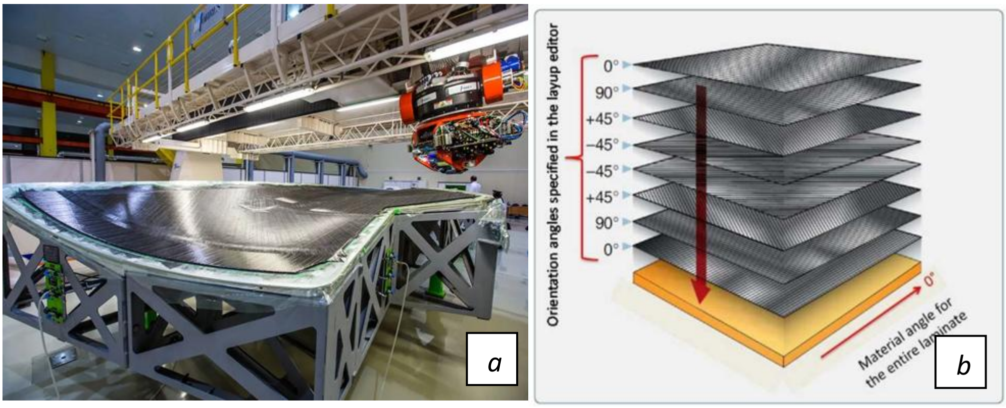

Fig. 1. Manufacturing technology from composite materials by forming fibers in one direction (a) and the structure of the part when forming fibers in different directions (b).

Therefore, given that the power parts of aircraft made of composite materials that come into contact with titanium alloys have different fiber arrangement structures, it is necessary to conduct research in the conditionally fixed contact of the main structural titanium alloys with different structures of composite materials. Given that parts of composite materials made of fiberglass in modern aircraft are mainly made for hatches and panels inside the aircraft, we will also take a sample of composite materials made of fiberglass with an equilateral structure.

The purpose of the study consists in determining the impact of damage caused by contact of titanium alloys with composite materials (carbon fiber and fiberglass) depending on the manufacturing technology of composite materials under vibration loads

Testing procedure. For studies on the wear resistance of titanium alloys with composite materials, the following variants of combinations of friction pair contacts were determined:

1. Titanium alloy Ti5Al5V5Mo1Cr1Fe with CFRP with ED-20 binder (predominantly one-sided direction of fiber formation);

2. Titanium alloy Ti5Al5V5Mo1Cr1Fe with CFRP with ED-20 binder (carbon 3K plaine fabric);

3. Titanium alloy Ti5Al5V5Mo1Cr1Fe with GFRP with EDT-69N binder (T-10-14 fabric);

4. Titanium alloy Ti6Al4V with CFRP with ED-20 binder (predominantly one-sided direction of fiber formation);

5. Titanium alloy Ti6Al4V with CFRP with ED-20 binder (carbon 3K plaine fabric);

6. Titanium alloy Ti6Al4V with GFRP with EDT-69N binder (fabric T-10-14).

The contact options of titanium alloys and composite materials cover more than 80 % of the contact combination options in the power structure elements of modern aircraft.

The tests were carried out according to the methodology presented in the work [4]. The samples were made of titanium alloys Ti6Al4V and Ti5Al5V5Mo1Cr1Fe with a diameter of 20 mm without surface treatment. The countersample was a metal sample on which the corresponding composite material was glued and processed on a lathe and grinding machine. The composite material with a one-sided direction was taken from a fragment of a defective aircraft wing panel, which was presented by the enterprise "Constanta Airlines" for research according to the contract No 2025/101/UA between the University and "Constanta Airlines". The contact occurred on a surface with a nominal contact area of 1 cm^2.

The tests were performed with a constant load of 6 MPa and a sample displacement amplitude of 125 μm. The test base was 300 thousand cycles. The oscillation frequency was 30 Hz and the test temperature was 16-20 ºC. Wear resistance studies were performed without lubricant in air. The samples before and after the tests were wiped with Antisilicone liquid and dried. The linear wear of the stationary sample was measured with an optimeter by taking values from 8 equilateral sections. The wear of the counter sample was determined by the difference in size before and after the tests. There were at least three experiments for each column of the histogram.

Analysis of wear resistance of titanium alloys with composite materials under conditions of nominally stationary contact. The test results are presented in Fig. 2. Analyzing the wear resistance of titanium alloys with composite materials with different structures of reinforcing fibers, it can be concluded that the one-sided fiber direction shows lower wear resistance characteristics than the equilateral one. The decrease in wear resistance of materials with one-sided fiber arrangement reaches up to 20 % when comparing the test results with fabric. The effect does not depend on the counterbody and with the titanium alloy Ti5Al5V5Mo1Cr1Fe the decrease in wear resistance of composite materials occurs by 19 %, and when tested with the titanium alloy Ti6Al4V by 12 %.

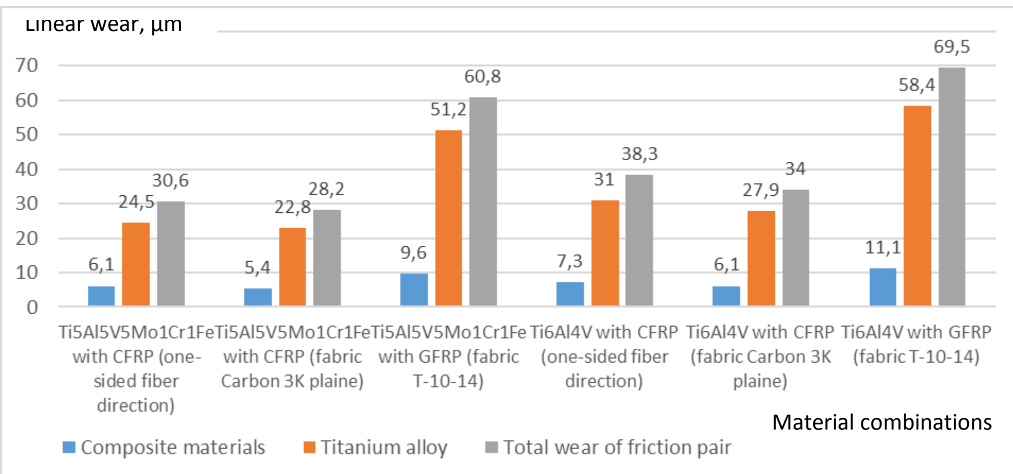

Fig. 2. Wear resistance of different variants of contact of titanium alloys with composite materials with different structures of arrangement of reinforcing fibers during studies in nominally fixed contact.

The decrease in wear resistance may be associated with easier destruction of the one-sided CFRP structure with Carbon 3K plaine fabric during the vibration (reversible) action of the titanium sample on the surface of the composite material. Epoxy resin, possibly, impregnates the fabric woven in the equilateral direction better than in the one-sided one due to the larger voids that the epoxy matrix fills during autoclave molding of the surface of the part. During one-sided molding, the fibers of the composite material fit more tightly to each other, which may make it difficult for the binder to penetrate between such fibers and prevent their better connection (Fig. 3). During the vibration action of the titanium alloy, due to the adhesion and compaction of titanium on the surface of the fibers of the composite material, their destruction occurs during the process of reversible movements and crumbling and, as a result, increased wear compared to the equilateral arrangement of woven carbon fibers.

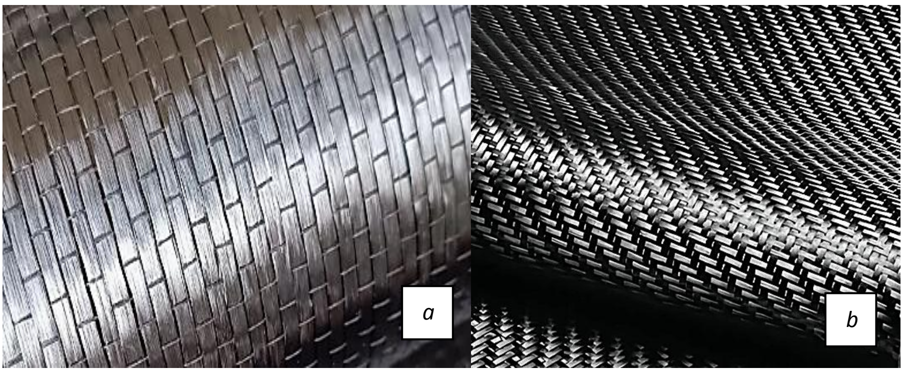

Fig. 3. Structure of composite materials formed by forming fibers in one direction (a) and in different directions (b).

The wear resistance of GFRP with T-10-14 fabric shows results of lower wear resistance than carbon fiber. Moreover, the wear resistance is lower with different variants of titanium alloy contact. The reduction in wear of fiberglass reaches 1.7-1.8 times compared to the wear resistance of carbon fiber in studies with Carbon 3K plaine fabric, which is explained by the abrasive action of glass particles in the friction zone that are formed during the destruction of the fabric under conditions of vibration loading and reversible movements of the samples. Fig. 4 presents photographs of the surfaces of composite materials after testing with titanium alloy Ti6Al4V. Analysis of the photos shows that the friction surface is covered with a layer of titanium oxide that is formed during the friction process.

When analyzing the total wear of the contact of a titanium alloy of the same type (Ti5Al5V5Mo1Cr1Fe or Ti6Al4V) with carbon fiber of different types of fabric directions, the difference in wear resistance is insignificant and lies within 10 %. A slight increase in the wear resistance of the total wear of the contact pair shows us that when forming the direction of fibers for the manufacture of aircraft parts, more attention should be paid to other methods of increasing the wear resistance of the friction pair than to the formation of a certain fiber structure in the contact zone. However, it can be proposed as a technological approach to form or glue the contact points of composite materials with a titanium alloy with a fabric with an equilateral arrangement of carbon fibers, which increases the total wear resistance of the joints by up to 10 %.

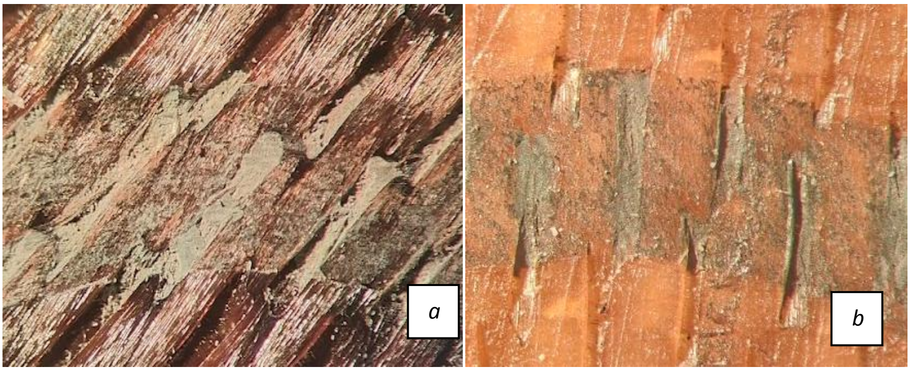

Fig. 4. Topographies of friction surfaces of CFRP composite materials with one-sided formation of carbon fibers (a) and GFRP (b) after testing with titanium alloy Ti6Al4V.

When comparing wear between titanium alloys Ti6Al4V and Ti5Al5V5Mo1Cr1Fe, one can clearly note increased wear resistance, up to 20 % of the Ti5Al5V5Mo1Cr1Fe alloy.

First, the increased wear resistance can be explained by the presence of larger alloying elements in the titanium alloy. The table of chemical composition of titanium alloys is presented in Table. 1. For example, such alloying elements as Mo, Cr, Fe are not present at all in the titanium alloy Ti6Al4V. The content of 5 % molybdenum, which is famous for its wear resistance [5-9], significantly increases the tribotechnical properties of any alloy and titanium alloy is no exception. Well, the increased content of vanadium and chromium also significantly affects the wear resistance of the titanium alloy Ti5Al5V5Mo1Cr1Fe.

Table 1.

Chemical composition of the studied titanium alloys

Titanium alloy	Content of chemical elements, %											
	Ti	Al	V	Mo	Cr	Fe	Zr	Si	O	C	N	H
Ti5Al5V5 Mo1Cr1Fe	remainder	4,74	5,04	5,57	0,81	0,98	0,30	0,15	0,18	0,10	0,05	0,015
Ti6Al4V	remainder	6,46	3,84	-	-	0,08	0,02	0,01	0,17	0,01	-	-

Thus, the increased tribotechnical properties of molybdenum are shown in works [6, 7]. The authors of [6] propose to use molybdenum for the restoration of rails of aircraft wing mechanization made of titanium alloy VT-22. In works [8, 9] the authors propose to use molybdenum coatings for cutting materials. In work [7] the author, having investigated spherical bearings, proposes to protect surfaces made of titanium alloy with vacuum-arc molybdenum coating, which allows to increase the wear resistance of friction surfaces by 20 %, while replacing the base material from X105CrMo17 with titanium alloy VT-22.

All these authors [6-8] note the ability of molybdenum to absorb internal energy and, as a consequence, reduce the dynamic load on surfaces that occurs during friction. Molybdenum in the process of friction under fretting corrosion conditions has high microplasticity, which affects the level of the amplitude-dependent area of internal friction. The low binding energy of impurity atoms with dislocations, the low threshold voltage for the start of operation of dislocation sources leads to the rapid multiplication of easily mobile dislocations under the action of cyclic loads. The mechanisms of hysteretic and microplastic internal friction provide the dissipation of the supplied mechanical energy with its conversion into heat, and are a mechanism for dislocation stress relaxation, i.e. a factor that reduces the dynamic tension of friction surfaces. Against the background of the action of diffusion mechanisms of relaxation internal friction and the development of strengthening due to dynamic strain aging, molybdenum exhibits high dislocation relaxation ability in a wide range of amplitudes of mutual displacement under alternating friction [7].

The increased wear resistance of the Ti5Al5V5Mo1Cr1Fe alloy compared to the Ti6Al4V alloy is noted in [10]. The authors explain this by the chemical activity of these two alloys. The Ti6Al4V alloy with a finely dispersed structure, which is obtained during the pressing process under conditions of reduced temperatures in the range of 800-550 ºC, exhibits lower corrosion resistance during free corrosion in a sulfuric acid environment compared to the Ti5Al5V5Mo1Cr1Fe alloy.

In [11], when studying the fretting resistance of titanium alloys under vibration conditions, the author established that the wear resistance of titanium alloys decreases when moving from low-strength titanium alloys to high-plastic and high-strength alloys. It was also determined that, along with the mechanical factor that determines the intensity of the development of fretting-corrosion fatigue processes, there is a competing chemical factor, the effect of which is associated with the destruction of friction surfaces under conditions of oxidative (corrosion) processes.

Analyzing the wear resistance of titanium alloys Ti5Al5V5Mo1Cr1Fe and Ti6Al4V, it can be stated that the titanium alloy Ti5Al5V5Mo1Cr1Fe has high corrosion resistance (due to alloying elements) on the one hand and increased strength characteristics (due to the finely dispersed structure due to low-temperature annealing) on the other hand, which in total gives increased wear resistance of 20 %. The wear resistance of titanium alloys is very strongly influenced by their heat treatment. Depending on whether it is a deformed titanium alloy or simply obtained by casting, the wear resistance can vary by up to 1.4 times, provided that the titanium alloy has enough alloying elements to change its physical and mechanical properties.

Thus, according to the author [12], the wear resistance of the titanium alloy Ti5Al5V5Mo1Cr1Fe can vary depending on the conditions of thermal exposure and annealing at different temperatures. The value of the surface microhardness HV can vary from 4.5 to 7.1 GPa, and the endurance limit σ_β from 1.2 to 1.7 GPa, which gives a difference in the wear resistance of the titanium alloy Ti5Al5V5Mo1Cr1Fe up to 50 % when the titanium alloy is studied in combination with a steel sample.

Conclusions. The increased wear resistance of composite materials compared to titanium alloys shows that the main attention in increasing the reliability and durability of the contact of aircraft parts in a conditionally fixed contact should be paid to titanium alloys, since their wear resistance is several times lower than the wear resistance of CFRP and GFRP due to their physical and mechanical characteristics. Uniform damage to parts made of polymer composite materials reinforced with carbon and glass fibers and another mechanism of their wear [7, 13, 14], due to epoxy binders, gives reason to believe that the main attention in increasing the wear resistance of the contact should be paid to titanium. In addition, titanium alloys easily change their surface properties under the influence of various technological factors. The change in the properties of the surface layer can reach 1000 times, which certainly affects the wear resistance and, as a consequence, the destruction processes of the Ti-

CFRP contact in aircraft under vibration conditions. Which can both increase the durability of the contact as a whole and lead to even greater destruction of the surfaces of the parts.

References

1. Gay D. Damage in Composite Parts; Failure Criteria. *Composite Materials*. 4th ed. Boca Raton, 2022. P. 285-308. URL: https://doi.org/10.1201/9781003195788-17

2. Chen W., Li Z. Additive manufacturing of titanium aluminides. *Additive Manufacturing for the Aerospace Industry*. 2019. P. 235–263. URL: https://doi.org/10.1016/b978-0-12-814062-8.00013-3

3. Akahori T. Effects of microstructure on the short fatigue crack initiation and propagation characteristics of biomedical α/β titanium alloys *Metallurgical and Materials Transactions A.* 2000. T. 31, № 8. C. 1949–1958. URL: https://doi.org/10.1007/s11661-000-0222-z

4. Vargel C. Fretting corrosion. *Corrosion of Aluminium*. 2020. P. 273–278. URL: https://doi.org/10.1016/b978-0-08-099925-8.00021-1

5. Khimko A. Fretting resistance of VT-22 alloy with aviation materials. *Problems of friction and wear.* 2006. Issue 46. P. 84-90.

6. Khimko A. Increasing the wear resistance of titanium alloy parts by plasma coatings. *Dissertation on Technical Sciences: 05.02.04* NAU. K, 2008. 182 p.

7. Khimko M. Increasing the wear resistance of spherical bearings using metal-polymer and polymer composite materials. *Dissertation on Technical Sciences: 05.02.04.* K. KAI. 2025. 244 p.

8 Klymenko I.S. Production, properties and application of molybdenum. *XXI International scientific and practical conference of students, postgraduates and young scientists "Actual problems of life of society".* 2024. URL: https://doi.org/10.32782/2222-5099.2024.4.36

9. Grechanyuk V. G. Copper and Molybdenum-Based Nanocrystalline Materials. *Metalofizika I noveishie tekhologii*. 2022. T. 44, № 7. C. 927–942. URL: https://doi.org/10.15407/mfint.44.07.0927

10. Abramova P.V. Effect of deformation-heat treatment of (α+β)-titanium alloys VT6 and VT22 on their corrosion resistance. *Bulletin of the Tomsk Polytechnic University Geo Assets Engineering.* 2023. T. 334, № 4. C. 89–102. URL: https://doi.org/10.18799/24131830/2023/4/4124

11. Duhota O. I. Scientific and technical foundations of increasing the durability of parts of aviation tribomechanical systems under the conditions of their fretting-contact interaction. *thesis.* 2019. URL: http://er.nau.edu.ua:8080/handle/NAU/37723

12. Alyabyev A., Dukhota A., Zelenkov I. Hydration and its influence on wear of titanium alloys during fretting corrosion. *Problems of friction and wear*: K. Technika, 1982. Vol. 21. P. 89-93.

13. Khimko M., Khimko A., Mnatsakanov R., Klipachenko V., Makarenko R. Wear resistance of polymer composite materials for spherical bearings. *Problems of friction and wear.* 2024. No. 2 (103). P. 29-42.URL: https://doi.org/10.18372/0370-2197.2(103).18670

14. Khimko M., Khimko A., Mnatsakanov R., Mikosyanchyk O. Influence of thermophysical properties of metal-polymer composite materials on wear resistance. *Problems of friction and wear.* 2024. No. 3 (104). P. 91-100.URL: https://doi.org/10.18372/0370-2197.3(104).18984

The article was received by the editors on February 12th, 2025.

Andrii Khimko – Candidate of technical sciences, associate professor, associate professor of Aircraft Continuing Airworthiness Department, State university KAI, 1 Lubomyra

Huzar Ave., Kyiv, Ukraine, 03058, E-mail: andreykhimko@ukr.net, https://orcid.org/0009-0009-8059-880X

Oksana Mikosianchik – Doctor of technical sciences, professor, Head of the Department of Applied Mechanics and Materials Engineering, State university KAI, 1 Lubomyra Huzar Ave., Kyiv, Ukraine, 03058, E-mail: oksana.mikos@ukr.net, https://orcid.org/0000-0002-2438-1333.

Marharyta Khimko – candidate of technical sciences, first deputy director of Air Company LLC “H3Operations”, Staronavodnytska Str., 6б, Kyiv city, Ukraine, 01015, E-mail: margarytakhimko@gmail.com, https://orcid.org/0009-0005-4364-5444

Filonenko Oleksandr – 1st year master's student, Aerospace Faculty, Aircraft Continuing Airworthiness Department, State university KAI, 1 Lubomyra Huzar Ave., Kyiv, Ukraine, 03058, E-mail: fiilonenko@icloud.com https://orcid.org/0009-0008-5140-3658

А.М. ХІМКО, О.О. МІКОСЯНЧИК, М.С. ХІМКО, О. ФІЛОНЕНКО

ЗНОСОСТІЙКІСТЬ ТИТАНОВИХ СПЛАВІВ ІЗ КОМПОЗИТНИМИ МАТЕРІАЛАМИ В ЗАЛЕЖНОСТІ ВІД ТЕХНОЛОГІЇ ЇХ ВИГОТОВЛЕННЯ В УМОВНО НЕРУХОМОМУ КОНТАКТІ

Титанові сплави та композитні матеріали (вуглецеве волокно та скловолокно) останнім часом широко використовуються в сучасних літаках та гелікоптерах. Контакт титанових матеріалів з полімерними силовими композитними матеріалами в умовах вібраційного навантаження супроводжується пошкодженням як титану, так і композитних матеріалів. У статті представлено вплив на зносостійкість контактуючих матеріалів залежно від способу їх виготовлення та складу композитного матеріалу. Встановлено, що при контакті титанових сплавів із полімерними композиційними матеріалами зносостійкість титанових сплавів нижче в 3-6 разів ніж вуглепластиків та склопластиків в умовах вібраційних навантажень та мікропереміщень, що пояснюється специфічними властивостями титанових сплавів в контакті із матеріалами GFRP та CFRP.

Визначено, що зносостійкість скловолокна в 1,7-1,8 рази нижча, ніж у вуглецевого волокна при випробуваннях із титановими сплавами при вібраційних навантаженнях. Встановлено, що загальна зносостійкість контакту Ti-CFRP збільшується на 10 % при формуванні тканини композиційного матеріалу в різних напрямках порівняно з односпрямованим формуванням. Також було встановлено, що зносостійкість сплаву Ti5Al5V5Mo1Cr1Fe більше до 20 % порівняно зі сплавом Ti6Al4V при випробуваннях з композитними матеріалами, що пояснюється підвищеним вмістом легуючих елементів та як наслідок фізико-механічних характеристик.

Ключові слова: титанові сплави, умовно нерухомий контакт, знос, вуглецеве волокно CFRP, скловолокно GFRP, пошкодження, аналіз, зносостійкість до фретингу.

Список літератури

1. Gay D. Damage in Composite Parts; Failure Criteria. *Composite Materials*. 4th ed. Boca Raton, 2022. P. 285-308. URL: https://doi.org/10.1201/9781003195788-17

2. Chen W., Li Z. Additive manufacturing of titanium aluminides. *Additive Manufacturing for the Aerospace Industry*. 2019. P. 235–263. URL: https://doi.org/10.1016/b978-0-12-814062-8.00013-3

3. Akahori T. Effects of microstructure on the short fatigue crack initiation and propagation characteristics of biomedical α/β titanium alloys *Metallurgical and Materials Transactions A*. 2000. Т. 31, № 8. С. 1949–1958. URL: https://doi.org/10.1007/s11661-000-0222-z

4. Vargel C. Fretting corrosion. *Corrosion of Aluminium*. 2020. P. 273–278. URL: https://doi.org/10.1016/b978-0-08-099925-8.00021-1

5. Хімко А.М. Фретингостійкість сплаву ВТ-22 з авіаційними матеріалами *Проблеми тертя та зношування*. 2006. Вип. 46. С. 84-90.

6. Хімко А.М. Підвищення зносостійкості деталей із титанових сплавів плазмовими покриттями. дис…канд. техн. наук. К. НАУ., 2008. 182 с.

7. Хімко М.С. Підвищення зносостійкості шарнірних підшипників застосуванням металополімерних та полімерних композиційних матеріалів. дис…канд. техн. наук К. КАІ. 2025. 244 с.

8 Клименко І.С. Одержання, властивості та застосування молібдену. *XXXI Міжнародна науково-практична конференція студентів, аспірантів та молодих учених «Актуальні проблеми життєдіяльності суспільства»*. 2024. URL: https://doi.org/10.32782/2222-5099.2024.4.36

9. Grechanyuk V. G. Copper and Molybdenum-Based Nanocrystalline Materials. *Metalofizika I noveishie teknologii*. 2022. Т. 44, № 7. С. 927–942. URL: https://doi.org/10.15407/mfint.44.07.0927

10. Abramova P.V. Effect of deformation-heat treatment of (α+β)-titanium alloys VT6 and VT22 on their corrosion resistance. *Bulletin of the Tomsk Polytechnic University Geo Assets Engineering.* 2023. Т. 334, № 4. С. 89–102. URL: https://doi.org/10.18799/24131830/2023/4/4124

11. Духота О. І. Науково-технічні основи підвищення довговічності деталей авіаційних трибомеханічних систем за умов їх фретинг-контактної взаємодії. *thesis.* 2019. URL: http://er.nau.edu.ua:8080/handle/NAU/37723

12. Alyabyev A., Dukhota A., Zelenkov I. Hydration and its influence on wear of titanium alloys during fretting corrosion. *Problems of friction and wear*: K. Technika, 1982. Vol. 21. P. 89-93.

13. Khimko M., Khimko A., Mnatsakanov R., Klipachenko V., Makarenko R. Wear resistance of polymer composite materials for spherical bearings. *Problems of friction and wear.* 2024. No. 2 (103). P. 29-42.URL: https://doi.org/10.18372/0370-2197.2(103).18670

14. Khimko M., Khimko A., Mnatsakanov R., Mikosyanchyk O. Influence of thermophysical properties of metal-polymer composite materials on wear resistance. *Problems of friction and wear.* 2024. No. 3 (104). P. 91-100.URL: https://doi.org/10.18372/0370-2197.3(104).18984

Хімко Андрій Миколайович - канд. техн. наук, доцент кафедри підтримання льотної придатності повітряних суден, КАІ, пр. Любомира Гузара, 1, м. Київ, Україна, 03058, E-mail: andrii.khimko@npp.nau.edu.ua https://orcid.org/0009-0009-8059-880X

Мікосянчик Оксана Олександрівна – док. техн. наук, професор, завідувач кафедри прикладної механіки та інженерії матеріалів, КАІ, пр. Любомира Гузара, 1, м. Київ, Україна, 03058, E-mail: oksana.mikos@ukr.net, https://orcid.org/0000-0002-2438-1333

Хімко Маргарита Сергіївна – канд. техн. наук, перший заступник директора авіаційної компанії ТОВ «H3Operations», вул. Старонаводницька, 6б, м. Київ, Україна, 01015, E-mail: margarytakhimko@gmail.com, https://orcid.org/0009-0005-4364-5444

Філоненко Олександр Євгенович - студент 1 року навчання магістратури, Аерокосмічного факультету, кафедри підтримання льотної придатності повітряних суден, КАІ, пр. Любомира Гузара, 1, м. Київ, Україна, 03058, E-mail: fiilonenko@icloud.com, https://orcid.org/0009-0008-5140-3658