УДК 620.178.16 DOI: 10.18372/0370-2197.1(110).20915

A. KHIMKO[1]*, O. POPOV*[1]*, M. KHIMKO*[2]

[1]State University "Kyiv Aviation Institute", Kyiv
[2]LLC Airline «H3Operations», Kyiv

EFFECT OF TEMPERATURE ON THE WEAR RESISTANCE TI6AL4V-CFRP/GFRP CONTACT UNDER VIBRATION CONDITIONS

A study of the influence of temperatures from minus 50 to plus 50 ºC on the contact of TI6AL4V-CFRP/GFRP materials under the influence of the vibration factor is presented. It was determined that at temperatures of minus 50 ºC the wear resistance of composite materials increased by 20-25%. When the temperature decreases, the epoxy resins that make up the matrix change their mechanical characteristics towards increasing hardness, mechanical strength, creep, etc. It was found that GFRP with glass fibers showed less results in increasing wear resistance at negative temperatures, since glass fibers are more sensitive to low temperatures than carbon fibers in CFRP. Increasing the brittleness of glass reinforcing fibers allowed to increase wear resistance by 20% overall. While materials with carbon fibers demonstrate an increase in wear resistance by 25%.

It was found that the wear resistance of the Ti6Al4V alloy during testing almost does not change. A slight increase in wear up to 3-5% on the one hand may indicate an error in the research during measurement, and on the other hand, the influence of the environment on the friction process.

The studies established the stability of the contact and the balance of wear of the power elements of the structures in the TI6AL4V-CFRP/GFRP contacts under vibration action and changes in the temperature conditions of the tests from minus 50 to 50 ºC. An increase in wear resistance up to 25% of materials based on epoxy resins and carbon and glass fibers is noted due to changes in the physical and mechanical properties of the matrix at negative temperatures up to minus 50 ºC.

Key words: *temperature, impact, titanium alloys, vibration, composite materials, wear, structure, fiberglass, carbon fiber.*

Introduction. Modern aircraft operate in various locations around the globe. Temperatures can range from minus 60 °C in the Arctic Circle to plus 60 °C in the equatorial African continent [1]. In addition, temperatures can vary significantly during aircraft operation. At an altitude of 10,000–12,000 meters, which is the norm for modern aircraft, the temperature ranges from minus 56 °C to minus 60 °C. At the same time, when an aircraft lands at Kuwait International Airport, where the air temperature in July is 56°C, the aircraft and its structure are exposed to significant temperature effects.

However, when aircraft are parked and waiting at airports under the influence of sunlight, the temperature on the surfaces of wings, fuselages, landing gear, etc. can reach 80-100 °C. There are also contact points near aircraft engines where exhaust and infrared radiation from the combustion chamber can also significantly raise the temperature of contact points of titanium alloys and composite materials up to 200 °C [2-3].

Therefore, to determine the temperature effect of the contact points of titanium alloys with composite materials of the GFRP and CFRP types, it is necessary to conduct appropriate tests.

As is known, the temperature conditions of operation of titanium alloys are significantly higher than those of aircraft operation. Thus, highly loaded parts and structures made of the Ti5Al5V5Mo1Cr1Fe alloy, which are manufactured by the deformation method, are capable of long-term operation at temperatures up to 350-400 ºC [4], and large-sized power structures of the airframe (spars, wing panels, ribs, stable landing gear) at temperatures up to 250-300 ºC.

The titanium alloy Ti6Al4V has even higher temperature strength characteristics. For stamped and welded parts made of this alloy, the operating temperature can be 400-450 ºC, and for large-sized welded and prefabricated aircraft structures operating under internal pressure, the operating temperature ranges are from minus 196 to plus 450 ºC [5].

For composite materials, the temperature range is usually lower and limited by the matrix composition. However, depending on the purpose and filling of the matrix material with additional elements in the form of metal powder, carbon nanotubes, or special ceramic materials with heat-resistant resins, it is possible to achieve operating conditions up to 400 ºC. But in general, the operating range of most GFRP and CFRP composite materials with epoxy binders is usually in the range from minus 50 to 250 ºC. For GFRP, the operating temperature is somewhat lower and is in the range from minus 50 to 150 ºC. Also, considering that these are polymer composite materials, according to [6] they are less temperature-resistant materials than metals, due to poorer heat removal from friction zones.

Therefore, taking into account the above information and analysis of the operating conditions of aircraft and the joints of parts made of titanium alloys with a structure made of GFRP and CFRP composite materials in accordance with contracts No. 2024/139/UA, No. 2025/88/UA, No. 2025/101/UA, we will determine the conditions for conducting research in the range from minus 50 to plus 50 °C. Research at negative temperatures was carried out with the assistance and within the accordance of report No. 2025/88/UA between Airlines LLC «KCEHA» and the State University «Kyiv Aviation Institute».

The purpose of the work is to determine the wear resistance of titanium alloy Ti6Al4V and composite materials GFRP/CFRP in contact under vibration loads at temperatures from minus 50 to plus 50 ºC.

Testing procedure. The methodology for conducting studies of the influence of temperature on the contact of titanium alloys with composite materials was in accordance with [7]. The methodology allows testing at negative temperatures on standard samples using liquid nitrogen. Since the temperature factor has a greater effect on polymer composite materials than on titanium alloys, only the Ti6Al4V alloy was determined for our studies, in accordance with the customer's conditions. This alloy is the most common structural material for aircraft power elements for manufacturers such as Boeing and Airbus.

The samples were made standard without surface treatment, with a nominal contact area of 1 cm^2. The counter sample was metal, onto which the corresponding GFRP and CFRP composite material was glued and processed on a lathe and grinding machine. The studies were performed with a constant load of 6 MPa, an amplitude of mutual displacements of 125 μm and a test base of 300000 cycles. The oscillation frequency was 30 Hz and the test temperature was minus 50 and plus 50 ºC.

The samples were cooled by supplying cooled nitrogen gas to the friction zone according to the method described in [7]. To prevent snow from sticking to the samples and to conduct research in water and ice environments, as well as simulating real operating conditions of joints in aircraft, the samples were first brought into contact at a temperature close to room temperature, the unit was started, and cooled air was supplied at the same time to reduce the temperature. The temperature was monitored by a remote-type thermometer. The temperature decrease graph from the start of the tests is shown in Fig. 1. The samples were heated using a construction hair dryer with the ability to adjust the temperature. To compare the test results, the samples were also heated simultaneously with the start of the fretting-corrosion machine. The temperature increase graph is also shown in Fig. 1. This test algorithm was determined from the analysis of the operating conditions of the aircraft's power structural elements, since the operation of the unit begins at takeoff at temperatures close to room temperature and decreases to negative temperatures at an altitude of 10-12 thousand meters. All other test conditions were the same as those described in the article [8].

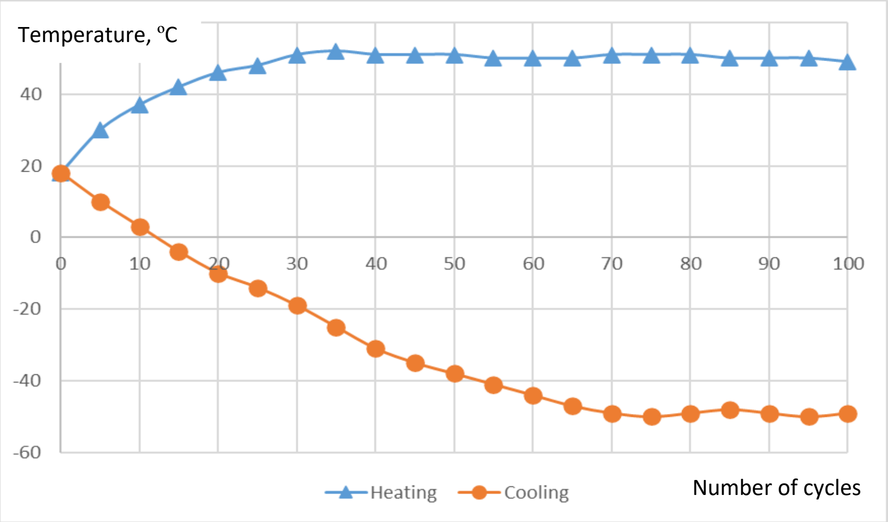

Fig. 1. Dependence of the rate of volumetric heating and cooling of titanium samples on the number of operating cycles during testing under vibration conditions.

From the graph (Fig. 1) it is seen that the temperature reduction to minus 50 ºC occurs at a number of cycles equal to 70 thousand, which corresponds to approximately 40 minutes of testing. This time was determined based on the analysis of the aircraft structure during operation. When the aircraft is on the ground, the temperature corresponds to a conditionally 20 ºC. When the aircraft takes off, the vibration action of the power elements of the structures begins at the ambient temperature. The aircraft reaches the operating level (9-12 thousand meters) approximately 20-30 minutes after the start of the flight, where the temperature corresponds to a conditionally minus 50 ºC. However, the parts and assemblies of the aircraft have a certain inertia and retain primary heat for some time (about 40 minutes) and only then level off in temperature. Therefore, based on the real operating conditions of the aircraft, such a scheme for cooling samples during tests under vibration conditions was implemented. The heating of the samples to the required temperature occurred much faster, about 25-30 thousand cycles, which corresponds to 13-15 minutes from the start of the tests. The heating rate is accelerated by the fact that during the tests, a certain temperature is released during friction, which helps in heating the samples.

Analysis of wear resistance test results at temperatures under vibration conditions. The test results are presented in Fig. 2, 3. Analyzing the wear resistance of materials at different temperatures, we can say that, as a rule, at negative temperatures, the wear of materials decreases [9], which is associated with a change in physical and mechanical properties. The hardness and resistance to damage during friction increase. However, in our case, when titanium alloy and composite materials GFRP and CFRP are in contact, this is partially manifested, but not for all materials.

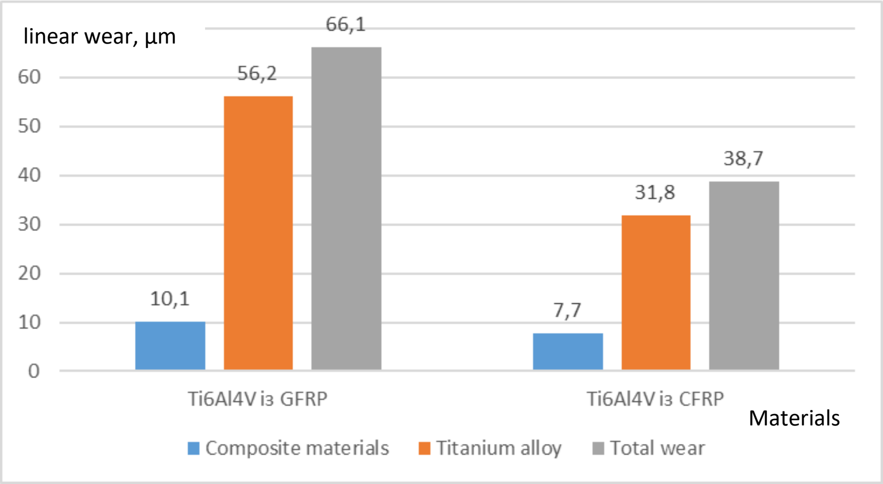

Fig. 2. Wear resistance of material combinations during testing under vibration conditions at a temperature of 50 ºC.

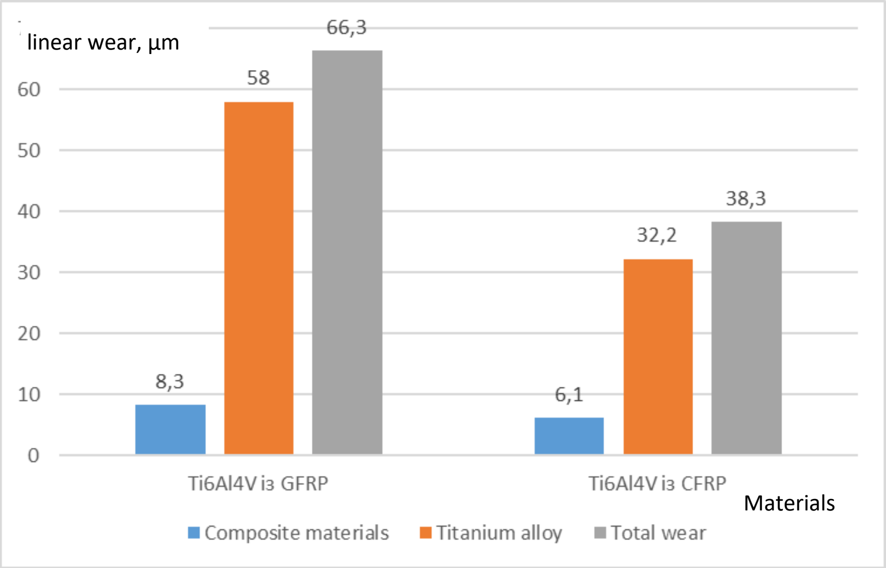

Fig. 3. Wear resistance of material combinations when tested under vibration conditions at a temperature of minus 50 ºC.

Analyzing the wear resistance of GFRP and CFRP composite materials, it can be stated that at temperatures of minus 50 ºC their wear resistance increased by 20-25%. When the temperature decreases, the epoxy resins that make up the matrix change their mechanical characteristics towards increasing hardness, mechanical strength, creep, etc., which positively affects the wear resistance of composite materials in general. Usually, in any epoxy material there is a limit where the materials become so strong that they begin to collapse from mechanical stress during friction. In our case, the temperature of minus 50 ºC is not a critical temperature for the matrix used to create aircraft structures, therefore, the indicators that characterize wear resistance increase.

From literary sources [9] it is known that the operating range for aviation composite materials GFRP and CFRP starts from minus 80-60 ºC. Therefore, the critical limit where the destruction of composite materials increases will be lower than minus 50 ºC.

The presence of reinforced fibers, both carbon and glass, only strengthens the mechanical performance of the epoxy matrix. Since the operating temperature range for reinforcing fibers is much wider than for the binder. It should be noted that the GFRP material with glass fibers showed less results in increasing wear resistance at negative temperatures, since glass fibers are more sensitive to low temperatures than carbon. Increasing the brittleness of glass reinforcing fibers allowed to increase the wear resistance of the GFRP material by 20 % in general. While the material with carbon fibers CFRP demonstrates an increase in wear resistance by 25 %.

The data are confirmed by the authors [9, 10] who conducted research on the influence of water and ultraviolet on composite materials based on carbon fiber. The authors determined the positive effect of negative temperatures on the wear resistance of the CFRP material to a certain limit, as well as a slight decrease in mechanical properties in the temperature range of 170-200 ºC due to changes in the properties of the binder in the composite material. But of course, the final tribological characteristics and the effect of temperature on them will depend on the chemical composition and structural filling of the matrices in the material.

In [10], it is shown that the properties of the CFRP material during thermal cycling are preserved in the range of 83-95 % of the primary properties of composite materials. Thus, with a regular change in temperature from minus 60 to 160 ºC, the mechanical properties of composite materials are preserved at the level of 91-95 %. And during thermal cycling in the temperature range of 150-200 ºC, the preservation of properties occurs at the level of 83-90 %.

The wear resistance of titanium alloy Ti6Al4V during testing almost does not change. Titanium alloys have much wider operating temperature ranges and do not change their properties as much as composite materials at negative temperatures. A slight increase in wear up to 3-5 % on the one hand may indicate an error in the research during measurement, and on the other hand may indicate the influence of the environment [11] on the friction process of titanium alloys.

During research at negative temperatures, the samples during the friction process were covered with frost and ice, which condenses on the metal surfaces of the sample and definitely gets into the friction zone (Fig. 4). Here, on the one hand, there is an influence of the air environment on the testing process, and on the other hand, there is a process of moisture and water entering the friction zone with its decomposition into hydrogen and oxygen, which accelerate reactions under fretting corrosion conditions.

Thus, in article [12] the author notes a decrease in wear and an increase in the friction coefficient during tests of titanium alloy VT3-1 in a nitrogen environment due to blocking the chemical oxidation reaction which is the main one during tests in fretting corrosion conditions. The author also notes a decrease in wear in an environment of inert gases helium and argon and an increase in wear in an oxygen environment.

In works [13-15] the authors note an increase in wear of titanium alloys due to hydrogenation of the surface with hydrogen and, as a result, an increase in the fragility of its surface during friction. However, tests at a temperature of minus 50 ºC slow down the hydrogenation processes.

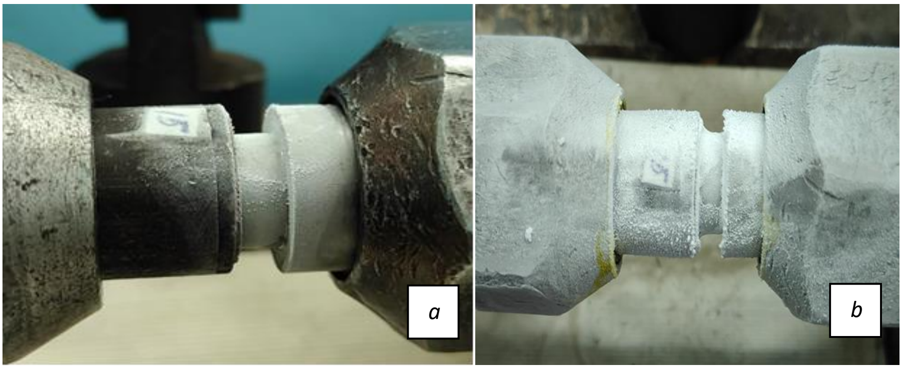

Fig. 4. Photos of samples during testing under vibration conditions at temperatures of minus 50 ºC at the beginning (a) and at the end (b) of the tests.

Thus, during the friction of titanium alloys with GFRP/CFRP composite materials, there is a relationship between the processes: increasing the mechanical properties of the alloys due to a decrease in temperature; processes of hydrogenation of titanium alloys due to the formation of oxygen and hydrogen in the friction zone; processes of blocking oxidation by nitrogen gas supplied to the friction zone; processes of oxidation of titanium alloys during fretting corrosion tests; and of course the mechanical and chemical effect of the products of destruction of composite materials on the friction process of titanium alloys. All these processes are probably in balance with each other, as evidenced by the change in wear of the titanium alloy up to 3%.

The total wear of the Ti6Al4V-GFRP/CFRP friction pair at different temperatures deserves special attention. The total wear resistance of the samples practically did not change both during studies at negative temperatures and during studies at 50 ºC. In the contact of composite materials and titanium alloy, due to the greater wear of the titanium alloy and the reduction in wear of the composite materials, the total contact remained constant in the Ti6Al4V-GFRP contact and decreased by 1,8 % in the Ti6Al4V-CFRP contact.

Conclusions. The conducted tests show the stability of contact and the balance of wear of the power elements of structures made of composite materials of aircraft in contact with titanium alloys under vibration and changes in temperature conditions of tests from minus 50 to 50 ºC. An increase in wear resistance of up to 25 % of composite materials based on epoxy resins and carbon and glass fibers is also noted due to changes in the physical and mechanical properties of the matrix at negative temperatures up to minus 50 ºC.

References

1. Khimko M., Khimko A., Mnatsakanov R., Mikosyanchyk O. Resource testing of modified plain bearings for the aviation industry. *Problems of tribology.* V.29, No. 2/112-2024, P.16-22. URL: https://doi.org/10.31891/2079-1372-2024-112-2-16-22

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. Additive Manufacturing of Titanium and Its Alloys. *Titanium Alloys.* 2024. P. 263–288. URL: https://doi.org/10.1142/9789811291487_0010

4. Khimko A.M. Fretting resistance of VT-22 alloy with aviation materials. *Problems of friction and wear*: *scientific and technical collections. K.: NAU*, 2006. Issue 46. P. 84 – 90.

5. Nishiyama S., Shirai Y., Fuji K. Mechanical Properties of Extruded Ti-6Al-4V Having Acicular α+β Microstructure Formed in Refined α Grains. *Proceedings of the 13th World Conference on Titanium. Hoboken, NJ, USA*, 2016. P. 581–584. URL: https://doi.org/10.1002/9781119296126.ch95

6. Chauhan A.K. Properties of Composite Materials. *Composite Materials. First edition.* Boca Raton, FL: CRC Press, 2021., 2020. P. 61–78. URL: https://doi.org/10.1201/9781003080633-3

7. GOST 23.21180 Ensuring wear resistance of products. *Method of testing materials for wear during fretting and fretting corrosion*. https://vsegost.com/Catalog/19/1934.shtml

8. Khimko A., Mikosianchik O., Khimko M., Filonenko O. Wear resistance of contact of titanium alloys with composite materials depending on the technology of their manufacturing under conditions of nominally fixed contact. *Problems of friction and wear.* 2025. No. 3 (108). P. 28-37. URL: https://doi.org/10.18372/0370-2197.3(108).20445

9. Moulder J. C., Hust J. G. Compatibility of Materials with Cryogens. *Materials at Low Temperatures*. 1983. P. 343–369. URL: https://doi.org/10.31399/asm.tb.mlt.t62860343

10. Batista N.L., Faria M.C.M., Jha K., Olivera P.C., Bothelho E.C. Influence of water immersion and ultraviolet weathering on mechanical properties of polyphenylene sulfide-carbon fiber composites / *Journal of thermoplastic composite materials*. 2013. No. 1. P. 1–17

11. Umanskyi O.P., Pugachevska E.P., Khimko A.M. Development of technology for applying new wear-resistant composite coatings to strengthen aircraft engine parts. *Aerospace Engineering and Technology*. 2009. No. 9. P. 38–44. http://nbuv.gov.ua/UJRN/aktit_2009_9_7

12. Dukhota O.I. Ensuring the operability of titanium alloys under fretting corrosion conditions. *dissertation for the degree of candidate of technical sciences in the specialty 05.02.04 - friction and wear in machines*. K. 1983. 207 p.

13. Seiersten M. Hydrogen Absorption in Cathodically Polarized Titanium Alloys. *ASME 2002 21st International Conference on Offshore Mechanics and Arctic Engineering, Oslo, Norway, 23–28 June 2002*. 2002. URL: https://doi.org/10.1115/omae2002-28580

14. Cavaliere P. Hydrogen Embrittlement: The Case of Titanium Alloys. *Hydrogen Embrittlement in Metals and Alloys. Cham*, 2025. P. 549–578. URL: https://doi.org/10.1007/978-3-031-83681-7_7

15. Lupu D. Hydrogen absorption in aluminum - magnesium - titanium alloys. *Metal–Hydrogen Systems.* 1982. P. 437–443. URL: https://doi.org/10.1016/b978-0-08-027311-2.50044-9

Received: February 04, 2026
Accepted: March 01, 2026
Published: April 09, 2026

Andrii Khimko – candidate of technical sciences, associate professor, associate professor of Air Tpansport Department, State university KAI, 1 Lubomyra Huzar Ave., Kyiv city, Ukraine, 03058, E-mail: andreykhimko@ukr.net, https://orcid.org/0009-0009-8059-880X

Popov Oleksandr – candidate of technical science, associate professor, head of the Air Tpansport Department, Kyiv Aviation Institute, Lybomyra Huzara av., 1, Kyiv city, Ukraine, 03058, E-mail: oleksandr.popov@npp.kai.edu.ua, https://orcid.org/0000-0003-1029-2767

Khimko Marharyta – candidate of technical sciences, first deputy Director of the airline “H3Operations” LLC, associate professor of Air Tpansport Department, Staronavodnytska str., 6b, Kyiv city, Ukraine, 01015, E-mail: m.khimko@h3ops.com, https://orcid.org/0009-0005-4364-5444

А.М. ХІМКО, О.В. ПОПОВ, М.С. ХІМКО

ВПЛИВ ТЕМПЕРАТУРИ НА ЗНОСОСТІЙКІСТЬ КОНТАКТУ TI6AL4V-CFRP/GFRP В УМОВАХ ВІБРАЦІЇ

Сучасні літаки в свої конструкціях масово використовують композиційні матеріали для того щоб зробити планер як можна легшим і як наслідок підвищити льотно-технічні характеристики. До таких матеріалів відносяться вуглепластики CFRP та склопластики GFRP. Деталі та вузли передових повітряних суден виготовляють із сплавів магнію, алюмінію та титану. Титановий сплав TI6AL4V займає особливе місце в авіабудуванні та використовується масово в конструкції силових деталей планерів літаків. Аналіз показує що контакт матеріалів TI6AL4V-CFRP/GFRP доволі розповсюджений а робота цих матеріалів під дією вібрації, яка є невід'ємною частиною всіх літаків, та температурних коливань призводить до пошкоджень цих з'єднань.

Представлено дослідження впливу температур від мінус 50 до плюс 50 ºС на контакт матеріалів TI6AL4V-CFRP/GFRP під дією вібраційного фактору. Визначено, що при температурах мінус 50 ºС зносостійкість композиційних матеріалів підвищилась на 20-25 %. При зниженні температури, епоксидні смоли з яких складається матриця, змінюють свої механічні характеристики у бік підвищення твердості, механічної міцності, повзучості та ін. що позитивно впливає на зносостійкість. Наявність армованих волокон як вуглецевих так і скляних лише зміцнює механічні показники епоксидної матриці. Встановлено, що GFRP із скляними волокнами показали менші результати по підвищенню зносостійкості при від'ємних температурах, оскільки скляні волокна більш чутливі до низьких температур ніж вуглецеві у CFRP. Підвищення крихкості скляних армуючих волокон дозволило в цілому композиційні матеріали підвищити зносостійкість на 20 %. В той час як матеріали із вуглецевими волокнами демонструють підвищення зносостійкості на 25 %.

Встановлено, що зносостійкість сплаву Ti6Al4V при випробуваннях майже не змінюється. Відбувається взаємозв'язок між процесами: підвищення механічних властивостей сплавів за рахунок зниження температури; процесами наводнення титанових сплавів за рахунок утворення кисню та водню в зоні тертя; процесами блокування окиснення газом азотом що подається в зону тертя; процесами окиснення титанових сплавів в процесі випробувань при вібраціях; ну і звичайно механічний та хімічний вплив продуктів руйнування композиційних матеріалів на процес тертя титанових сплавів. Всі ці процеси мабуть знаходяться в балансі між собою про що свідчить зміна зносу титанового сплаву до 3 %.

Дослідженнями встановлено сталість контакту та рівновагу зносу силових елементів конструкцій із композиційних матеріалів повітряних суден в контактах із титановими сплавами при вібраційної дії та зміни температурних умов випробувань від мінус 50 до 50 ºС. Відмічається збільшення зносостійкості до 25 % композиційних матеріалів на основі епоксидних смол та вуглецевих і скляних волокон за рахунок зміни фізико-механічних властивостей матриці при від'ємних температурах до мінус 50 ºС.

Ключові слова: *температура, вплив, титанові сплави, вібрація, композиційні матеріали, зношування, структура, склопластик, вуглепластик.*

Список літератури

1. Khimko M., Khimko A., Mnatsakanov R., Mikosyanchyk O. Resource testing of modified plain bearings for the aviation industry. Problems of tribology. V.29, № 2/112-2024, P.16-22. URL: https://doi.org/10.31891/2079-1372-2024-112-2-16-22

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. Additive Manufacturing of Titanium and Its Alloys. Titanium Alloys. 2024. P. 263–288. URL: https://doi.org/10.1142/9789811291487_0010

4. Хімко А.М. Фретингостійкість сплаву ВТ-22 з авіаційними матеріалами *Проблеми тертя та зношування: наук.-техн. зб.* К.: НАУ, 2006. Вип. 46. С. 84 – 90.

5. Nishiyama S., Shirai Y., Fuji K. Mechanical Properties of Extruded Ti-6Al-4V Having Acicular α+β Microstructure Formed in Refined α Grains. *Proceedings of the 13th World Conference on Titanium. Hoboken, NJ, USA,* 2016. P. 581–584. URL: https://doi.org/10.1002/9781119296126.ch95

6. Chauhan A.K. Properties of Composite Materials. *Composite Materials. First edition. Boca Raton, FL: CRC Press,* 2021., 2020. P. 61–78. URL: https://doi.org/10.1201/9781003080633-3

7. ГОСТ 23.21180 Забезпечення зносостійкості виробів. Метод випробувань матеріалів на зношування при фретингу та фретинг-корозії. https://vsegost.com/Catalog/19/1934.shtml

8. Khimko A., Mikosianchik O., Khimko M., Filonenko O. Wear resistance of contact of titanium alloys with composite materials depending on the technology of their manufacturing under conditions of nominally fixed contact. *Проблеми тертя та зношування.* 2025. № 3 (108). С. 28-37. URL: https://doi.org/10.18372/0370-2197.3(108).20445

9. Moulder J. C., Hust J. G. Compatibility of Materials with Cryogens. *Materials at Low Temperatures.* 1983. P. 343–369. URL: https://doi.org/10.31399/asm.tb.mlt.t62860343

10. Batista N.L., Faria M.C.M., Jha K., Olivera P.C., Bothelho E.C. Influence of water immersion and ultraviolet weathering on mechanical properties of polyphenylene sulfide-carbon fiber composites. *Journal of thermoplastic composite materials.* 2013. №1. P. 1–17

11. Уманський О.П., Пугачевська Е.П., Хімко А.М. Розробка технології нанесення нових зносостійких композиційних покриттів для зміцнення деталей авіаційних двигунів. *Авіаційно-космічна техніка та технологія.* 2009. № 9. С. 38–44. http://nbuv.gov.ua/UJRN/aktit_2009_9_7

12. Духота О.І. Забезпечення працездатності титанових сплавів в умовах фретинг-корозії. *дис. на здоб. канд. техн. наук за спеціальністю 05.02.04 – тертя та зношування в машинах.* К. 1983. 207 с.

13. Seiersten M. Hydrogen Absorption in Cathodically Polarized Titanium Alloys. *ASME 2002 21st International Conference on Offshore Mechanics and Arctic Engineering, Oslo, Norway, 23–28 June 2002.* 2002. URL: https://doi.org/10.1115/omae2002-28580

14. Cavaliere P. Hydrogen Embrittlement: The Case of Titanium Alloys. *Hydrogen Embrittlement in Metals and Alloys. Cham,* 2025. P. 549–578. URL: https://doi.org/10.1007/978-3-031-83681-7_7

15. D. Lupu Hydrogen absorption in aluminum - magnesium – titanium alloys. *Metal–Hydrogen Systems.* 1982. P. 437–443. URL: https://doi.org/10.1016/b978-0-08-027311-2.50044-9

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

Попов Олександр Вікторович - канд. техн. наук, завідувач кафедри авіаційного транспорту Державного університету КАІ, пр. Любомира Гузара, 1, м. Київ, Україна, 03058, E-mail: oleksandr.popov@npp.kai.edu.ua, https://orcid.org/0000-0003-1029-2767

Хімко Маргарита Сергіївна – канд. техн. наук, доцент кафедри авіаційного транспорту Державного університету КАІ, перший заступник директора Авіакомпанії ТОВ «НЗОПЕРЕЙШІНС», вул. Староноводницька, 6б, м. Київ, Україна, 01015, E-mail: margarytakhimko@gmail.com, https://orcid.org/0009-0005-4364-5444