УДК 620.178.16 DOI: 10.18372/0370-2197.2(107).20057

A. KHIMKO[1], O. MIKOSIANCHYK[1], R. MNATSAKANOV[1], S. BESPALOV[2], V. TOKARUK[1]

[1]State University "Kyiv Aviation Institute", Ukraine
[2]National Academy of Sciences of Ukraine

ANALYSIS OF DAMAGE TO AIRCRAFT PARTS MADE OF TITANIUM ALLOYS AND INCREASE OF THEIR WEAR RESISTANCE BY GAS-THERMAL COATINGS

The damage analysis of aircraft parts made of titanium alloys is carried out. Damage resulting from cyclic loads in the form of wear is shown. Gas-thermal coatings based on nickel for protection and restoration of parts made of titanium alloys are analyzed. The results on fretting resistance of some coatings that were applied by plasma method are carried out. It is established that the most fretting-resistant are coatings based on BK, as well as a molybdenum coating. It is theoretically determined that with an increase in temperature in the friction zone, the logarithmic decrement of the molybdenum coating increases more than that of nickel-based coatings. It is established that due to the high hardness of the BK type coating, it is possible to protect titanium parts of high rigidity, where the main operational factor is friction. In cases where wear of parts is combined with other loads such as bending, torsion, stretching, the optimal choice will be a molybdenum coating on parts made of titanium alloys.

Key words: *titanium alloys, fretting corrosion, wear, coatings, plasma method, damage, analysis, fretting resistance.*

Introduction. Titanium alloys are increasingly used in modern mechanical engineering and aircraft construction. High corrosion resistance, corrosion-mechanical strength, erosion-cavitation resistance, specific strength, non-cold brittleness, non-magnetic and a number of other physical and mechanical characteristics allow titanium alloys to be considered as materials that combine the properties of various materials. This makes it possible to manufacture units and mechanisms from mutually weldable titanium alloys of one or two grades, where the operating conditions require the use of a number of different materials, often non-weldable or incompatible, for example, due to contact corrosion [1, 2].

The aviation industry uses titanium alloys due to their: specific strength, heat resistance, corrosion resistance, etc. Titanium alloys are used to manufacture: skins of supersonic aircraft; power parts of aircraft and helicopters - engine bodies, pipelines, chassis units, spars, wings, wing mechanization monorails, couplings, etc.; many fasteners - rivets, bolts, screws, nuts, etc.; a number of gas turbine engine parts - disks, air compressor blades, compressor rotor [3]. For almost all of these parts, vibration is an accompanying factor of normal operation, and fretting corrosion [4] is one of the main damages that determines their performance - resource. In general, it can be noted that fretting wear affects parts that operate in a variety of conditions of vibration-contact loading. First of all, this is a diverse range of contacting loads and the possibility of relative vibration displacements between the articulated surfaces. The development of physical and chemical processes in the contact zone, and therefore the nature and intensity of wear, mainly depend on these factors.

Fig. 1 shows aircraft parts made of titanium alloys damaged by fretting corrosion as a result of operation. The pattern of fretting corrosion development is influenced by a number of factors – amplitude of movement, specific load, oscillation frequency, contact shape of mating parts, etc. [4]. Changes in these factors lead to a change in the processes at the friction contact, which is manifested in the nature of surface damage. Knowledge of the role of various factors, availability of data on the nature of the processes depending on the mechanochemical materials will allow a scientifically sound choice of the material of the mating surfaces for restoring parts, and will also bring some clarity to the methodology for choosing means of combating fretting corrosion.

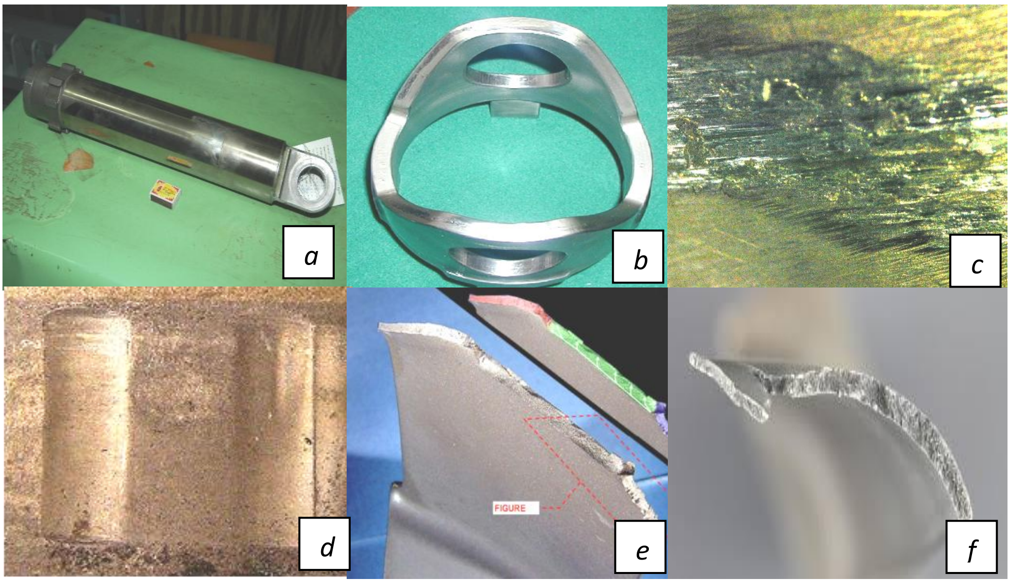

Fig. 1. Parts made of titanium alloys damaged by fretting corrosion during operation:
a – front landing gear rod of the aircraft made of VT-22 alloy; b – landing gear lock grip made of VT-22 alloy; c – damage topography of the landing gear lock grip; d – damage to the rail of the flaps retraction mechanism of the An-72 aircraft; e, f – damage to the compressor blade of the CFM-56 gas turbine engine.

Application of protective wear-resistant coatings is one of the most effective means of combating fretting wear. At present, thermal spray coatings are widely used in almost all branches of mechanical engineering, production of building structures, energy, engine building, aerospace, and other branches of new technology. With the help of coatings, it is possible to solve many problems: increasing weather resistance, operational durability, adhesion strength of the coating to the base, heat resistance, erosion resistance, protective properties and chemical resistance to ensure a calendar resource [5].

One of the actively developing areas is the plasma spraying method [6, 7]. Possessing high spraying productivity, this technological method allows applying coatings with a wide range of characteristics, as well as using them to restore the dimensions of worn parts.

The purpose of the study is analyzing the wear resistance of thermal spray coatings under fretting corrosion conditions and to select the optimal coating for the restoration of titanium alloy parts.

Testing procedure. The tests were conducted on a vibration-simulating setup using a plane-to-plane contact scheme.

Cylindrical rollers 20 mm made of VT-22 (a+b system type Ti-Al-Mo-V-Fe-Cr) titanium alloy was used as samples for spraying thermal spray coatings. The counter-sample in all tests was made of 95Х18Ш steel with a hardness of HRC 45-50 units. The test samples were mated along the surface, which was a closed ring with a nominal contact area of 0.5 cm^2, an internal diameter of 11 mm, and an external diameter of 13.6 mm.

The coatings were applied on a UPU-3D plasma unit. Before application, the surface was preparatorily processed: grinding and sanding. The thickness of the applied coatings was 600 μm, followed by mechanical processing to a value of 500 μm, including the sublayer. The studies of the change in linear wear and wear intensity of coatings were conducted in air under friction without lubricant. No preliminary running-in of samples was performed. In order to increase the accuracy and reliability of the study results, the number of tested samples was at least three per point. The study of fretting resistance was conducted on gas-thermal coatings and VT-22 alloy. The test conditions were as follows: the amplitude of mutual displacement of samples was 175 μm, specific load was 20 MPa, cyclic frequency was 30 Hz, the bulk temperature of samples at the beginning of the experiment was 20 ^{o}C, the test base was 500 thousand cycles, the environment was air.

Analysis of wear resistance of thermal spray coatings under fretting corrosion conditions. The test results are presented in Fig. 2. As can be seen from the graphs, all plasma thermal spray coatings are 2 to 6 times more fretting resistant than titanium alloy VT-22. The coating ПС12НВК-01 is less wear-resistant among plasma coatings. The high wear of this coating is due to the fact that it contains 35% tungsten carbide. During friction, high-hardness oxides are formed, which act as an abrasive material. The lowest wear was shown by molybdenum and ВК20 coatings. The high fretting resistance of the ВК20 coating is due to its high hardness (about 14 GPa).

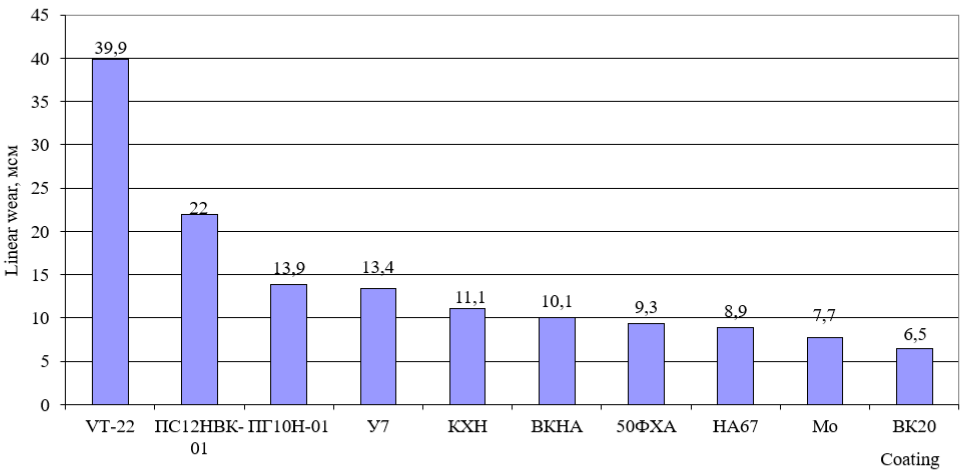

Fig. 2 Wear resistance of plasma gas-thermal coatings and titanium alloy VT-22 during testing under fretting corrosion conditions.

However, this property of the coating imposes certain requirements on its use for restoring parts made of titanium alloys. These parts are subject to various types of loading during operation. Most parts, in addition to wear, also work on bending, twisting, stretching, etc. Spraying such a hard coating on a relatively soft base of titanium alloys can lead to its chipping and cracking. In addition, it is necessary to adequately select the mating material.

The sufficiently high wear resistance of the plasma coating of molybdenum can be explained by the fact that finely dispersed oxides are formed during friction, which act as a solid lubricant (fig. 3a). This is confirmed by the established friction coefficient, which is minimal during friction of the molybdenum coating and corresponds to 0.31. Also, the high wear resistance of molybdenum can be explained by the fact that with an increase in temperature in the friction zone from 20 to 170 ºC, the logarithmic decrement [8] (damping capacity) of the molybdenum alloy increases more than that of other nickel-based coatings [9]. These data are repeatedly confirmed by the results of long-term studies [9, 10]. In addition to high wear resistance, the molybdenum coating has an elastic modulus closest to titanium alloys, which will clearly have a positive effect under cyclic and bending loads.

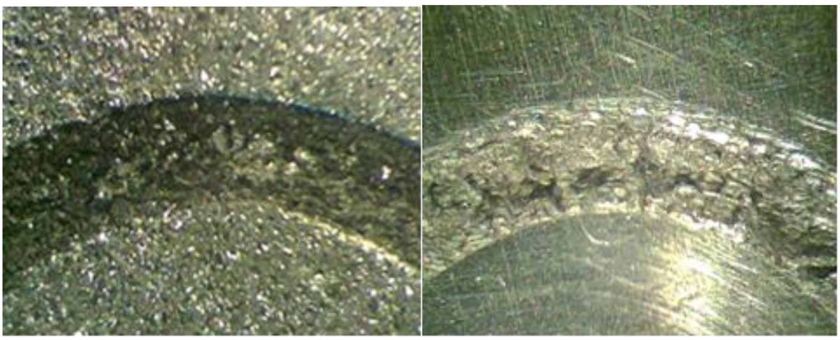

Fig. 3. Topography of friction tracks of gas-thermal coatings of molybdenum (a) and titanium alloy VT-22 (b), after fretting corrosion tests.

During friction of the titanium alloy on the counter sample, there was a constant transfer of titanium to the 95Х18Ш steel, which explains the high wear, and the friction actually occurred of titanium on titanium, due to its specific properties [1, 11]. In the initial period of testing, after a small number of cycles, the friction coefficient increases significantly. However, with a further increase in the duration of tests, the friction coefficient drops sharply. The initial growth stage can be in the range from a dozen oscillation cycles to several thousand cycles. The ambiguity of the change in the friction coefficient already at the early stages of fretting corrosion indicates that when the load-amplitude parameters of friction change, the leading processes of contact interaction change, the nature of which remains insufficiently clear.

Conclusions. Thus, based on the conducted research, it can be concluded that the most recommended coating for restoring worn areas of titanium alloy parts is molybdenum coating. It showed some of the most acceptable results in fretting resistance. Also, the least wear is shown by materials of the ВК series, due to high hardness and, as a consequence, wear resistance. However, on titanium parts, they should be used sparingly or subsequent processing by high-temperature methods should be used.

References

1. 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

2. Titanium Sponge Production and Processing for Aerospace Applications / C. R. V. S. Nagesh et al. *Aerospace Materials and Material Technologies*. Singapore, 2016. P. 73–89. URL: https://doi.org/10.1007/978-981-10-2134-3_4

3. Titanium Alloys for Aerospace Applications / M. Peters et al. *Titanium and Titanium Alloys*. Weinheim, FRG, 2005. P. 333–350. URL: https://doi.org/10.1002/3527602119.ch13

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. Thermal Sprayed Coatings. *The Protective Coatings User's Handbook*. 3rd ed. 2016. P. 113–141. URL: https://doi.org/10.5006/37605-ch05 .

6. Ružbarský J., Panda A. Thermal Spraying. *Plasma and Thermal Spraying*. Cham, 2016. P. 49–57. URL: https://doi.org/10.1007/978-3-319-46273-8_6

7. Мікосянчик О.О. Thermo-kinetic model for assessment of durability of contact surfaces under lubricating in non-stationary mode of operation. *Problems of Friction and Wear*. 2017. No. 1(74). URL: https://doi.org/10.18372/0370-2197.1(74).11436

8 Шевеля В.В., Дворук В.И., Радченко А.В. Modulation of metal surface abrasive tribocleaning. *Proceedings of the National Aviation University*. 2016. Vol. 6, no. 1-2. URL: https://doi.org/10.18372/2306-1472.6.9718

9. Roshan R., Patel S. K. NiTi plasma spray coating. *Nickel-Titanium Smart Hybrid Materials*. 2022. P. 151–172. URL: https://doi.org/10.1016/b978-0-323-91173-3.00013-4

10. Kralya V.A., Khimko A.N., Borodii V.N. Wear resistance of plasma coatings for a constant work of friction. *Strength of Materials*. 2007. Vol. 39, no. 5. P. 523–528. URL: https://doi.org/10.1007/s11223-007-0058-5

11. Khimko A.M. Wear resistance of materials under reversal and one-directed friction sliding *Proceedings of National Aviation University*. 2011. Vol. 46, no. 1. URL: https://doi.org/10.18372/2306-1472.46.2088

Стаття надійшла до редакції 19.02.2025

Andrii Khimko – Candidate technical of 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.

Rudolf Mnatsakanov – Doctor of Technical Sciences, Professor, Professor of Aircraft Continuing Airworthiness Department, State university KAI, 1 Lubomyra Huzar Ave., Kyiv, Ukraine, 03058, E-mail: mnatsakanov@ukr.net, https://orcid.org/0000-0001-5035-2432.

Serhii Bespalov – Doctor of Technical Sciences, Senior Researcher, Scientific Secretary of the Sector of Physical, Technical and Mathematical Sciences of the Scientific and Organizational Departmentof the Presidium of the National Academy of sciences of Ukraine, st. Volodymyrska, 54, Kyiv city, Ukraine, 02000, tel.: +380442396444, E-mail: bespalov@nas.gov.ua, https://orcid.org/0000-0002-6664-8614

Vitalii Tokaruk – Candidate technical of Sciences, associate professor in Aircraft Continuing Airworthiness Department, State university KAI, 03058, Ukraine, Kyiv, ave. Lubomir Husar, 1, tel.number: +380444067658, E- mail: vitalii.tokaruk@npp.nau.edu.ua https://orcid.org/0000-0002-1965-1765

А.М. ХІМКО, О.О. МІКОСЯНЧИК, Р.Г. МНАЦАКАНОВ, С.А. БЕСПАЛОВ, В.В. ТОКАРУК

АНАЛІЗ ПОШКОДЖЕНЬ АВІАЦІЙНИХ ДЕТАЛЕЙ З ТИТАНОВИХ СПЛАВІВ ТА ПІДВИЩЕННЯ ЇХ ЗНОСОСТІЙКОСТІ ГАЗОТЕРМІЧНИМИ ПОКРИТТЯМИ

Представлені авіаційні деталі з титанових сплавів які зазнали пошкодження в процесі експлуатації. Аналіз показав, що одним із найвпливовіших факторів який спричиняє пошкодження є вібраційні навантаження. Визначено що одним із найпопулярніших методів захисту та відновлення титанових деталей є газотермічні покриття. Визначено та проаналізовано зносостійкість деяких покриттів, що були нанесені плазмовим методом. Проведено їх випробування на зносостійкість в умовах фретинг-зношування. Результати порівнювали з літературними даними. Встановлено, що найбільш стійкими до фретингу є покриття серії ВК, а також молібден. Визначено, що при виборі покриття потрібно враховувати декілька факторів, а не тільки зносостійкість. Це залежить від пошкодженої деталі та умов її експлуатації та навантажуваності. Теоретично встановлено, що з підвищенням температури в зоні тертя логарифмічний декремент молібденового покриття збільшується більше, ніж газотермічні покриття на основі нікелю та заліза. Визначено, що для деталей які працюють на вигін, кручення, та ін. разом із фретинг-зношуванням краще підходить покриття молібдену, а для більш жорстких деталей підходить покриття на базі керамічних складових – як найбільш зносостійких.

Ключові слова: титанові сплави, фретинг-корозія, зношування, покриття, плазмовий метод, пошкодження, аналіз, фретинг-стійкість.

Список літератури

1. 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

2. Titanium Sponge Production and Processing for Aerospace Applications / C. R. V. S. Nagesh et al. *Aerospace Materials and Material Technologies*. Singapore, 2016. P. 73–89. URL: https://doi.org/10.1007/978-981-10-2134-3_4

3. Titanium Alloys for Aerospace Applications / M. Peters et al. *Titanium and Titanium Alloys*. Weinheim, FRG, 2005. P. 333–350. URL: https://doi.org/10.1002/3527602119.ch13

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. Thermal Sprayed Coatings. *The Protective Coatings User's Handbook*. 3rd ed. 2016. P. 113–141. URL: https://doi.org/10.5006/37605-ch05 .

6. Ružbarský J., Panda A. Thermal Spraying. *Plasma and Thermal Spraying*. Cham, 2016. P. 49–57. URL: https://doi.org/10.1007/978-3-319-46273-8_6

7. Мікосянчик О.О. Thermo-kinetic model for assessment of durability of contact surfaces under lubricating in non-stationary mode of operation. *Problems of Friction and Wear*. 2017. No. 1(74). URL: https://doi.org/10.18372/0370-2197.1(74).11436

8 Шевеля В.В., Дворук В.И., Радченко А.В. Modulation of metal surface abrasive tribocleaning. *Proceedings of the National Aviation University*. 2016. Vol. 6, no. 1-2. URL: https://doi.org/10.18372/2306-1472.6.9718

9. Roshan R., Patel S. K. NiTi plasma spray coating. *Nickel-Titanium Smart Hybrid Materials*. 2022. P. 151–172. URL: https://doi.org/10.1016/b978-0-323-91173-3.00013-4

10. Kralya V.A., Khimko A.N., Borodii V.N. Wear resistance of plasma coatings for a constant work of friction. *Strength of Materials*. 2007. Vol. 39, no. 5. P. 523–528. URL: https://doi.org/10.1007/s11223-007-0058-5

11. Khimko A.M. Wear resistance of materials under reversal and one-directed friction sliding *Proceedings of National Aviation University*. 2011. Vol. 46, no. 1. URL: https://doi.org/10.18372/2306-1472.46.2088

Хімко Андрій Миколайович - канд. техн. наук, доцент кафедри підтримання льотної придатності повітряних суден, КАІ, пр. Любомира Гузара, 1, м. Київ, Україна, 03058, тел.: +380444067658, 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, тел.: +38 044 406 77 70, E-mail: oksana.mikos@ukr.net, https://orcid.org/0000-0002-2438-1333

Мнацаканов Рудольф Георгійович – док. техн. наук, професор, професор кафедри підтримання льотної придатності повітряних суден, КАІ, пр. Любомира Гузара, 1, м. Київ, Україна, 03058, тел.: +380444067770, E-mail: rudolf.mnatsakanov@npp.nau.edu.ua https://orcid.org/0000-0001-5035-2432

Беспалов Сергій Анатолійович - док. техн. наук, старший науковий співробітник, учений секретар сектору фізико-технічних і математичних наук науково-організаційного відділу Президії НАН України, вул. Володимирська, 54, м. Київ, Україна, 02000, тел.: +380442396444, E-mail: bespalov@nas.gov.ua, https://orcid.org/0000-0002-6664-8614

Токарук Віталій Володимирович – канд. техн. наук, доцент кафедри підтримання льотної придатності повітряних суден, КАІ, пр. Любомира Гузара, 1, м. Київ, Україна, 03058, тел.: +380444067658, E-mail: vitalii.tokaruk@npp.nau.edu.ua https://orcid.org/my-orcid?orcid=0000-0002-1965-1765