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Increasing the durability of the Ti-GFRP/CFRP contact with a layer of wear-resistant polymer composite coatings under vibration load conditions

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Abstract

The development of aviation and the improvement of the flight characteristics of aircraft and helicopters requires the use of CFRP carbon fibers and GFRP fiberglass in power structures. The vibration load factor is an integral part of the aircraft design. With vibrations, a contact that we thought was nominally stationary begins to move at the micro level over time. Movement between parts is sufficient for the catastrophic development of fretting-corrosion wear of contacting parts, followed by the development of fatigue cracks and structural failure. Therefore, it is very important to pay attention to increasing the durability of contact made of Ti-GFRP/CFRP materials under vibration loads, since as a rule, these are power parts of aircraft, damage to which significantly reduces the reliability of the structure and increases the risk of fatigue cracks, especially in parts made of titanium alloys. One method of increasing the durability of the Ti-GFRP/CFRP contact is the use of intermediate "sacrificial" materials that are triggered during operation and replaced during repairs, but protect the contact from damage. The paper analyzes wear-resistant composite materials and determines what materials F4K15M5 and ZX550 are most suitable for this. It was found that during tests in the Ti-F4K15M5-GFRP system, the metal surface is completely protected by spreading an intermediate material on the surface. The mechanisms of wear of intermediate materials and their effect on contact under vibration loads have been determined.

Keywords: vibrations, titanium alloys, wear-resistant polymer materials, CFRP carbon fiberglass, GFRP fiberglass, durability, analysis, fretting corrosion.

Introduction

Ti-GFRP/CFRP material contact is increasingly common in modern aircraft where ultra-light and heavy-duty materials are used. The development of aviation and the improvement of the flight characteristics of aircraft and helicopters requires the use of CFRP carbon fibers and GFRP fiberglass in power structures. These parts are used to make wing panels, fuselage power elements, brackets and levers, etc. At the same time, the tendency to replace all steel parts in aircraft with titanium alloy is realized on modern Boeing and Airbus aircraft. Even power fasteners in modern aircraft are made of titanium alloys. Therefore, the contact of titanium alloys with power composite materials is increasingly found both in aircraft and in technology, where high strength characteristics are required with a low weight of the structure [1, 2].

At the same time, the factor of vibration loads is an integral part of the aircraft design. With vibrations, a contact that we thought was nominally stationary begins to move at the micro level over time. A movement between parts of a few microns is already sufficient for the catastrophic development of fretting-corrosive wear of contacting parts, followed by the development of fatigue cracks and structural failure. Therefore, it is very important to pay attention to increasing the durability of contact made of Ti-GFRP/CFRP materials under vibration loads, since as a rule, these are power parts of aircraft, damage to which significantly reduces the reliability of the structure and increases the risk of fatigue cracks, especially in parts made of titanium alloys.

Taking into account the latest trends in aviation tribology to replace metal parts and friction pairs operating at specific loads up to 300 MPa with tribological polymer composite materials, the issue of contact protection of structural Ti-GFRP/CFRP can be considered using modern wear-resistant composite materials with high tribological characteristics.

Literature review

Wear-resistant composite materials, in turn, can be divided into those that operate at increased loads of up to 300 MPa with reinforced fibers [3] and replace the metal friction pair according to their characteristics and into those that do not have reinforcement [4] and act as a lubricating layer on friction surfaces. The latter have PTFE and functional additives in the form of solid lubricants and reinforcing nanoparticles for the required physical and mechanical characteristics and operate in load ranges up to 50 MPa. It is such composite materials that are advisable for use in the Ti-GFRP/CFRP contact under vibration loads or under the development of fretting-corrosion processes. The undoubted advantage of wear-resistant composite materials is their flexibility in obtaining a certain composition with different fillers to obtain the necessary characteristics that allow replacing traditional liquid or paste-like lubricant when rubbing under conditions of fretting development. The composition of wear-resistant polymer composite materials, as a rule, includes the following types [4]: PEEK+PTFE+graphite+MoS_2 (high wear resistance under dry friction), UHMWPE+graphite+PTFE (low coefficient of friction in wet environment), PA6/PA66+graphite+PTFE (bushings and gears when working with pulsations), RI+graphite+PTFE (low coefficient of friction and heat resistance up to 250 ºC), polyoxymethylene+PTFE+MoS_2 (high tribological characteristics under dry friction), POM+graphite+PTFE (bushings and bearings up to 0.1 m/s, vibration loads), etc.

Thus, in the work [5], the authors, studying PTFE-based coatings during fretting corrosion, found that an increase in the normal load to 600 N increases the destruction of tribological films of polymeric composite materials without reinforcement. Studies show that the process of degradation of the coating under the influence of mechanical and chemical influences occurs due to the breaking of molecular chains and the emergence and spread of microcracks that cause the separation of PTFE coating particles.

The authors of the work [6] found that the lowest coefficient of friction under vibration loads of 0.091 was established with a mixture of PEEK and PTFE (70 %) with the addition of 10 % carbon fibers and 20 % graphite. It is also determined that the use of carbon fibers 20 % together with graphite 10 % allows obtaining the smallest wear value of 1.9 · 10-7 mm^3/Nm in the same matrix.

The authors note an increase in the wear resistance of the POM material with the addition of graphite and molybdenum disulfide under fretting conditions [7]. It has been determined that the addition of graphite and MoS_2 has a positive effect on impact strength in fretting corrosion tests. Microstructural study shows that the addition of 2-6 % solid lubricants increases the tribological characteristics of POM by 2 times.

The author of the work [8], studying polymeric composite materials based on PTFE, found that the addition of tin bronze microparticles in the composition of 30 % show excellent tribological characteristics at a load of 33 N and a frequency of 1 Hz or at a load of 81 N and a frequency of 0.75 Hz. The authors found that when tested under vibration conditions, the load and frequency become inversely proportional to the coefficient of friction.

The analysis of literature sources [3-8] showed that the most common are wear-resistant polymer composite material, which in their composition replace tribological films, materials with the addition of PTFE, graphite and MoS_2 in certain proportions, and functional additives (carbon nanotubes, talc, metal particles, PEEK) to obtain the necessary strength characteristics. PTFE and MoS_2 form a thin tribological layer on the surface, reducing adhesion and wear, while graphite stabilizes friction at moderate temperatures and retains properties under high loads. Thus, the analysis shows that fillers (PTFE+graphite+MoS_2) in PEEK matrices provide maximum wear resistance and self-lubrication over a wide range of friction modes.

Purpose

The purpose of the work is to increase the durability of the Ti-GFRP/CFRP contact by using modern wear-resistant composite materials under vibration load conditions.

Objects of research and experimental conditions

When choosing wear-resistant polymer composite materials for the protection of the Ti-GFRP/CFRP contact, first of all, you need to pay attention to the fact that most materials are used in techniques with certain strength characteristics, for which reinforcing fibers are introduced into the composition of polymers or more durable plastic is used as a matrix. In the case of T-GFRP/CFRP contact, only a layer of wear-resistant polymer composite materials is required between the power structural elements of aircraft, therefore, only materials with high tribological characteristics should be selected for protection.

In the paper [4], the author noted that wear-resistant polymer composite materials F4K15M5 are the basic tribological layer for many articulated bearings. The material F4K15M5, which consists of PTFE material (fluoroplastic-4) with 15 % graphite and 5 % MoS_2, has increased wear resistance, which is 1000 times higher than unfilled PTFE and a lower coefficient of friction [9]. Among the filled grades of PTFE-4, it has the most favorable friction and wear characteristics, and the material F4K15M5 is the best among them in terms of tribological parameters. Its analogues are Dyneon TFM-1600 G5, Ecoflon 2 (SKF), F4G15M5, as well as materials using another base PEEK+15%C+5%MoS_2, PI+15%C+5%MoS_2, UHMPE+15%C+5%MoS_2.

Among the commercial wear-resistant polymer composite materials that are widely used in mechanical engineering and have similar characteristics is the ZX550 material from Zedex. The ZX550 composite material has the best wear resistance characteristics among the materials of this company and consists of a PTFE base with the addition of 15 % graphite, 5 % MoS_2, 10 % glass fibers (E-glass) and 10 % fluorides (BaF_2, CaF_2) or bronze powder. The addition of glass fibers provides an increase in the strength and shape retention of polymer composite materials, while fluorides and bronzes expand the operating temperature range and increase the damping properties of the polymer during cyclic movements (vibration, fretting processes).

Thus, for testing the increase in the durability of the contact wear resistance contact Ti-GFRP/CFRP under vibration loads, we use materials F4K15M5 and ZX550. In Table. 1. Some physical and mechanical characteristics of wear-resistant polymer composite materials are presented.

Since the surface roughness of GFRP/CFRP materials is greater on titanium alloys, it is logical to assume that if there is a layer of materials F4K15M5 and ZX550 between the Ti-GFRP/CFRP contact, there will actually be a slippage between the selected polymer composite materials and the titanium alloy.

Table 1

Physical and Mechanical Characteristics of Wear-Resistant Polymer Composite Coatings Tested in Experiments

№	Indicators	F4K15M5 PTFE +15% Graphite +5 % MoS_2	Zedex ZX-550 PTFE +15% Graphite +5% MoS_2 +10–20% E-glass +5–10% BaF_2/CaF_2/bronze
1	Density, g/cm^3	2,20-2,24	2,25-2,230
2	Hardness Shore D	58-62	60-65
3	Dry friction coefficient	0,05-0,08	0,05-0,12
4	Tensile strength, MPa	18-22	20-25
5	Compressive strength, MPa	60-75	80-100
6	Operating temperature range, ºC	-100…+260	-250…+240
7	Bending modulus, MPa	500-600	800-1000

So, for the test, discs were made of ZX550 and F4K15M5 materials with a thickness of 0.5 mm and glued to GFRP material. The counter-sample was the Ti5Al5V5Mo1Cr1Fe material, which is the most common titanium alloy for the power parts of Antonov aircraft.

The conditions for conducting resource tests were as follows:

1. The test base for contact was determined at 300 thousand km. cycles.
2. The damage assessment was determined by determining the arithmetic mean of eight sections of friction tracks according to the scheme according to GOST 23.211-80.
4. The frequency of oscillations was 30 Hz.
5. The amplitude of oscillations was 125 μm and was determined from accelerated test conditions to intensify processes under vibrations.
6. The load for all subjects was 10 MPa.
7. All tests were carried out at a temperature of 16 to 20 °C.

Analysis of the tests performed and evaluation of the durability of the Ti-GFRP/CFRP contact

The test results are presented in Fig. 1, taking into account the wear of polymer composite materials. The analysis of the wear resistance of materials shows that wear-resistant polymer composite materials perfectly protect the friction surface of titanium alloy Ti5Al5V5Mo1Cr1Fe. When tested in the Ti-F4K15M5-GFRP system, the metal surface is completely protected by smearing on the surface of the composite material (Fig. 2 a). Ti-ZX550-GFRP is 30 % lower than in tests with a layer of material F4K15M5, but on the surfaces of the titanium alloy we have damage from the action of reinforced E-glass fibers.

Chemical analysis of the surface of the tribological film F4K15M5 (Fig. 2 b) shows the presence of areas with dark spots on the surface. The analysis shows that there is a gradual operation of polymeric composite materials due to the constant processes of smearing and tearing of the polymer and the action (Table 2) of oxygen on the composition of the film. Increased activation of the tribological layer is also shown by the total wear of friction surfaces (Fig. 1).

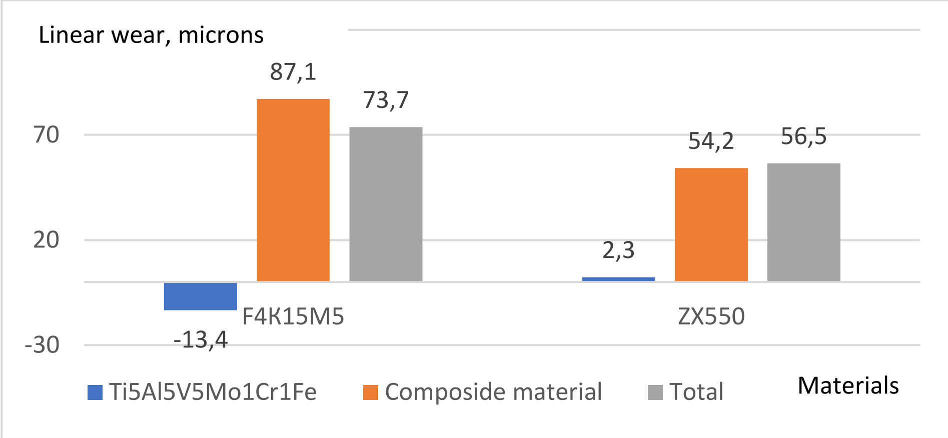

Fig. 1. Wear resistance of polymer composite materials paired with Ti5Al5V5Mo1Cr1Fe when tested under vibration load conditions

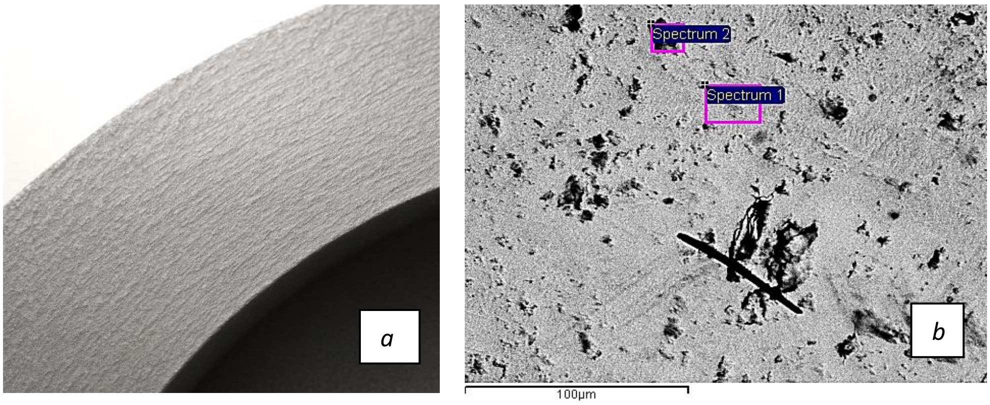

Fig. 2. Topographies of friction surfaces of titanium alloy Ti5Al5V5Mo1Cr1Fe (a) and chemical composition of tribological film sections (b) on the surface after vibration tests with F4K15M5 material.

Table 2

Chemical analysis of the friction surface with F4K15M5 material after vibration tests (Fig. 2 b), %

Spectrum	S	F	O	Mo	S	Ti	Si
Spectrum 1	38,2	26,7	11,3	6,5	5,1	7,8	1,2
Spectrum 2	25,4	16,4	20,3	4,5	4,2	21,1	5,8

During the sliding friction of materials Ti5Al5V5Mo1Cr1Fe with F4K15M5 under vibration conditions, micro irregularities of the titanium alloy come into contact with the PTFE-based material that is part of the composition and its introduction into the metal surface by cutting and adhering a softer surface to a harder surface of the alloy. Under loads and reverse movements, particles of polymer material F4K15M5 set with their subsequent rupture during stretching, which leads to the formation of a tribological film on the surface of the titanium alloy (Fig. 3a). The tribological film protects the surface of the titanium alloy from the contact of the reinforcing fibers of the GFRP material [10]. It includes wear particles of the material F4K15M5 (PTFE, MoS_2, graphite), which are mixed with each other and smeared on the surface of the titanium alloy with the addition of oxygen and the formation of additional structures. PTFE material provides a coefficient of friction in the range of 0.04-0.07, and graphite and MoS_2 petals stabilize friction, fill voids and absorb vibration loads from fretting processes and energy conversion into temperature. When the tribological layer that is self-lubricating is formed, friction goes into a mode with a chaotic breakdown and repeated growth of micro welds without sudden changes in the coefficient of friction. In the process of friction, the tribological layer is triggered by oxygen and periodic contact of oxygen with the surface of titanium. There is abrasive-adhesive wear of the metal surface and in the future contact of reinforced fibers on the surface of the titanium alloy. In general, properly selected materials of wear-resistant polymer composite materials stabilize the operation of the Ti-GFRP/CFRP contact with the intermediate layer and minimize the wear of Ti5Al5V5Mo1Cr1Fe and GFRP materials.

When Ti5Al5V5Mo1Cr1Fe materials come into contact with ZX550, the wear mechanism is almost the same, but increased physical and mechanical characteristics (greater hardness and modulus of elasticity) and the presence of E-glass and fluoride-bronze complex in the composition of reinforced fibers contribute to a more active action of oxygen on the surface of the titanium alloy with the formation of additional TiO_2 oxides as part of the tribological film. Fiberglass increases the strength of the tribological layer, reduces the depth of secondary plastic deformation and inhibits the increase in cracks in the film. Fluorides increase physical and mechanical characteristics for stress damping during vibration loads, and bronze particles stabilize tribological characteristics when the temperature in the friction zone rises [11].

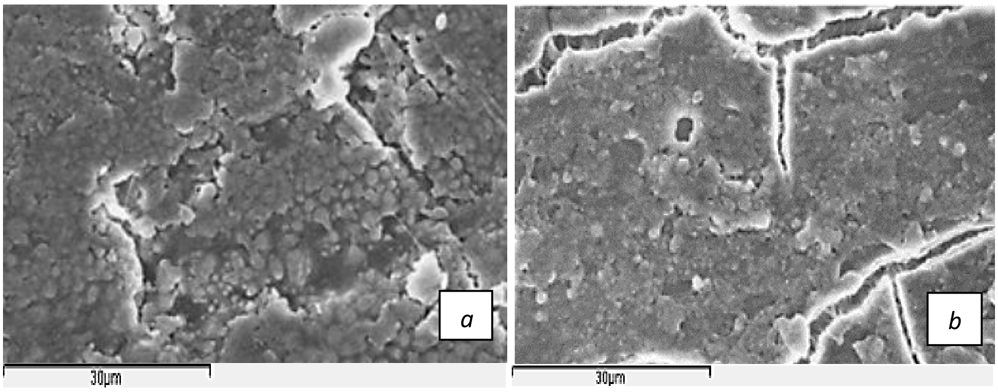

Fig. 3. Topography of the tribological layer formed on the surface of the titanium alloy Ti5Al5V5Mo1Cr1Fe by friction with polymer wear-resistant composite materials F4К15М5 (a) and ZX550 (b) under vibration loads

Due to the increased strength characteristics of the tribological layer, cracks appear on the surface (Fig. 3b), and the wear of the titanium alloy (Fig. 1) and the coefficient of friction increases to 0.05-0.08 in comparison with friction with the material F4K15M5, where the coefficient of friction was 0.04-0.07.

Conclusions

Thus, the analysis of test results and wear mechanisms of Ti-GFRP/CFRP contacts with intermediate layers of wear-resistant polymer composite materials under vibrations shows that the F4K15M5 material protects the contact of titanium alloys in contact by 30% more than the use of ZX550 material under fretting conditions at a load of 10 MPa, but is triggered faster. When exposed to vibration loads on the aircraft structure of about 10 MPa, we can recommend the material F4K15M5 in the contact system Ti-F4K15M5-GFRP/CFRP, which will give guaranteed protection of materials for some time, and in case of long-term operation or exposure to vibrations with a load of more than 20 MPa, we can recommend Zedex ZX550, which will be a kind of balance in damage and tripping of all contact materials Ti-ZX550-GFRP/CFRP. In addition, it is possible to carry out additional protection of the surface of titanium alloy or non-metallic coatings (oxidation, phosphating, passivation) or increase the wear resistance of the surface, for example, by chemical heat treatment (nitriding, carburizing), which showed excellent results in terms of wear resistance to fretting corrosion in the contact protection system Ti-GFRP/CFRP.

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References

1. Tareq M.A. Al-Quraan, Andrii Khimko, Margaryta Khimko, Oksana Mikosianchyk, Rudolf Mnatsakanov, Oleksandr Yakobchuk Increasing the Wear Resistance of Titanium Alloys in Plain Bearings with Galvanic and Vacuum-Arc Coatings. *Tribology in Industry.* Vol. 48, 1 (2026), p. 72-82. https://doi.org/10.24874/ti.2043.10.25.11 [English]

2. Chernets M.V., Romanenko E.O., Kornienko A.O., Chernets Yu.M. Methodological Foundations of Calculation of Metal and Metal-Polymer Plain Bearings: Contact Strength, Wear, Durability. Tom. 3. *Metal-polymer transmissions.* – Kyiv: NAU, 2022. – 250 p. [Ukrainian]

3. Chen Y. L., Lei Y. L., Zhang Y. Aircraft Composite Structures Fatigue Durability Test Method. *Advanced Materials Research.* 2014. Vol. 941-944. P. 1558–1561. URL: https://doi.org/10.4028/www.scientific.net/amr.941-944.1558 [English]

4. 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 [English]

5. Xu, M.H. Zhu, Z.R. Zhou, Fretting wear behavior of PTFE-based bonded solid lubrication coatings. *Thin Solid Films,* V. 457, Issue 2, 2004, Pages 320-325, https://doi.org/10.1016/j.tsf.2003.10.008 [English]

6. Li, Y.; Chen, Y.; Guo, Y.; Bian, D.; Zhao, Y. Tribological Behavior of PEEK/PTFE Composites Reinforced with Carbon Fibers and Graphite. *Materials* 2022, 15, 7078. https://doi.org/10.3390/ma15207078 [English]

7. Ramanjaneyulu, G., and Rajendran, R., Study of Wear Behaviour of POM/Graphite and POM/MoS_2 Composites, *SAE Technical Paper* 2017-28-1988, 2017, https://doi.org/10.4271/2017-28-1988 [English]

8. Charfi A, Neili S, Kharrat M, Dammak M. Tribological behaviors of PTFE-based composites filled with bronze microparticles. *Journal of Thermoplastic Composite Materials.* 2019. 34(12): 1639-1653. https://doi.org/10.1177/0892705719875203 [English]

9. Zygmunt R. Adhesion and wear in miniature plastic bearings. *Wear* 1991. 142, no. 1 185–93. http://dx.doi.org/10.1016/0043-1648(91)90160-v [English]

10. Khimko A., Popov O., Khimko M. Efect of temperature on the wear resistance TI6AL4V-CFRP/GFRP contact under vibration conditions. *Friction and wear problems.* 2026. No 1 (110). Pp. 4-12. URL: https://doi.org/10.18372/0370-2197.1(110).20915 [English]

11. Khimko A. M., Khimko M. S., Popov O. V., Klipachenko V. V. Estimation of the stress-strain state of composite materials for hinged bearings. *Problems of friction and wear.* 2025. № 1 (106). Pp. 4-16. URL: https://doi.org/10.18372/0370-2197.1(106).19819 [Ukrainian]

Хімко А.М., Мікосянчик О.О., Хімко М.С., Кліпаченко В.В. Підвищення довговічності контакту Ti-GFRP/CFRP прошарком зносостійких полімерних композиційних покриттів в умовах вібраційного навантаження

Розвиток авіації та підвищення льотно-технічних характеристик літаків та вертольотів вимагає застосування вуглепластиків CFRP та склопластиків GFRP в силових конструкціях. Фактор вібраційних навантажень є невід'ємною частиною конструкції повітряного судна. При вібраціях контакт який ми вважали номінально нерухомим починає з часом рухатись на мікрорівні. Переміщення між деталями достатньо для катастрофічного розвитку фретинг-корозійного зношування контактуючих деталей із наступним розвитком втомних тріщин та руйнування конструкції. В роботі проведено аналіз зносостійких композиційних матеріалів та визначено, що найбільше підходять для цього матеріали Ф4К15М5 та ZX550. Встановлено, що при випробуваннях в системі Ti-Ф4К15М5-GFRP поверхня металу захищена повністю за рахунок намазування на поверхню проміжного матеріалу. При випробуваннях із матеріалом ZX550 сумарний захист контакту Ti-ZX550-GFRP на 30 % нижче ніж при випробуваннях із прошарком матеріалу Ф4К15М5 але на поверхнях титанового сплаву маємо пошкодження від дії армованих волокон E-glass. Визначено механізми зношування проміжних матеріалів та їх вплив на контакт при вібраційних навантаженнях. Встановлено, що при впливі вібраційних навантажень до 10 МПа можна рекомендувати матеріал Ф4К15М5 в системі контактів Ti-Ф4К15М5-GFRP/CFRP, який дасть гарантований захист матеріалів на деякий час, а при довготривалої роботи та навантаженні більше 20 МПа можна рекомендувати фірми Zedex ZX550, який буде своєрідним балансом в пошкодженнях та спрацюваннях всіх матеріалах контакту Ti-ZX550-GFRP/CFRP.

Ключові слова: вібрації, титанові сплаві, зносостійкі полімерні матеріали, вуглепластик CFRP, склопластик GFRP, довговічність, аналіз, фретинг-корозія