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THE INFLUENCE OF CORROSIVE AND AGGRESSIVE ENVIRONMENTS ON THE CONTACT OF ALUMINUM AND TITANIUM ALLOYS WITH CFRP UNDER VIBRATION LOADING CONDITIONS

A study of the influence of the corrosive environment of seawater and an aggressive alkaline environment on the contact of the aluminum alloy D16T and the titanium alloy Ti6Al4V in a pair with the composite material CFRP under the action of the vibration factor is presented. Catastrophic destruction of the Al-CFRP contact in the conditions of the alkaline environment KOH with pH 11 was established. It was determined that the alloy D16T is very sensitive to changes in the environment. When tested in a NaCl solution, its wear increased by 1.4 times. The wear of the titanium sample decreased due to the presence of water and a humid environment in the friction zone, which lubricated the friction surfaces in some places. Temperatures of 20 ºC did not allow the processes of hydrogenation of the titanium alloy surface to occur, and as a result of the test, we record a decrease in wear by 1.09 times compared to the study in air. It has been established that the wear of the D16T material in salt water is a complex phenomenon that combines chemical corrosion and mechanical abrasion, which is often called three-component or combined corrosion. Mechanical loads caused by vibration additionally accelerate the destruction process, since the worn surface becomes even more susceptible to the aggressive effects of salts. Titanium alloys are much more resistant to the marine environment. It has been determined that high pH values actively affect the D16T and Ti6Al4V materials, sometimes leading to the destruction of passivating oxide films that naturally form on the materials. Catastrophic destruction of the D16T alloy shows chemical degradation and dissolution in an alkaline environment, which increases the wear of the material by more than 4 times.

Key words: *vibration, conditionally fixed contact, D16T, titanium alloy, wear, carbon fiber CFRP, damage, analysis, aggressive environments, corrosion.*

Introduction. For aircraft operating in marine or oceanic environments, maintenance requirements may be increased due to the aggressive effects of salt water and high humidity. This is usually regulated by documents developed by aircraft manufacturers, as well as international and national aviation regulatory authorities such as EASA or FAA. Corrosion-related standards and recommendations, such as ASTM, also play an important role.

Thus, when operating Antonov type aircraft near the coast of seas and oceans, the regulations and regulatory documents of the aircraft developer provide for an increase in the frequency of maintenance by 3-6 times, depending on the operating conditions and type of aircraft [1]. A similar situation occurs for Boeing family aircraft, but the frequency of maintenance there increases by 2-4 times, depending on the type of aircraft [2]. The more new materials (titanium, composite materials) are used in aircraft, the less the impact of the corrosive environment on the airframe structure and the less often it is necessary to increase maintenance. Anti-corrosion treatment and measures to slow down corrosion creep do not guarantee total protection [3, 4].

The places of contact of aircraft power structures with aluminum alloys are especially damaged. This is another reason why in new developments and new types of aircraft they are moving away from aluminum and steel parts, replacing them with composite materials and titanium alloys [5].

Thus, in the work [6], the author, analyzing the damaged areas of the elements of the Antonov family of aircraft, came to the conclusion that corrosion damage to the elements of aircraft operated in marine and humid climates accounts for 70 % of all defects. The most damaged are the aluminum power structures of aircraft located in the middle of the fuselage and wing. Fig. 1 and 2 present photos of the destruction of the power elements of the structures of Antonov aircraft in humid and marine climates [4].

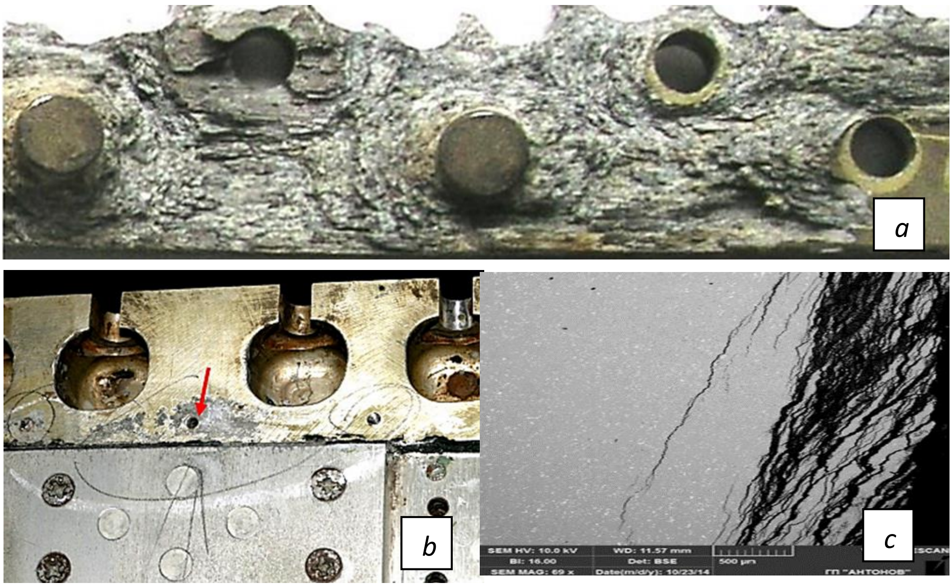

Fig. 1. Topography (a) and metallography (c) of delamination corrosion failure of an aircraft structural element made of B95T alloy in a tropical climate and the wing connector profile (b) of an An-12 aircraft in a marine climate [6].

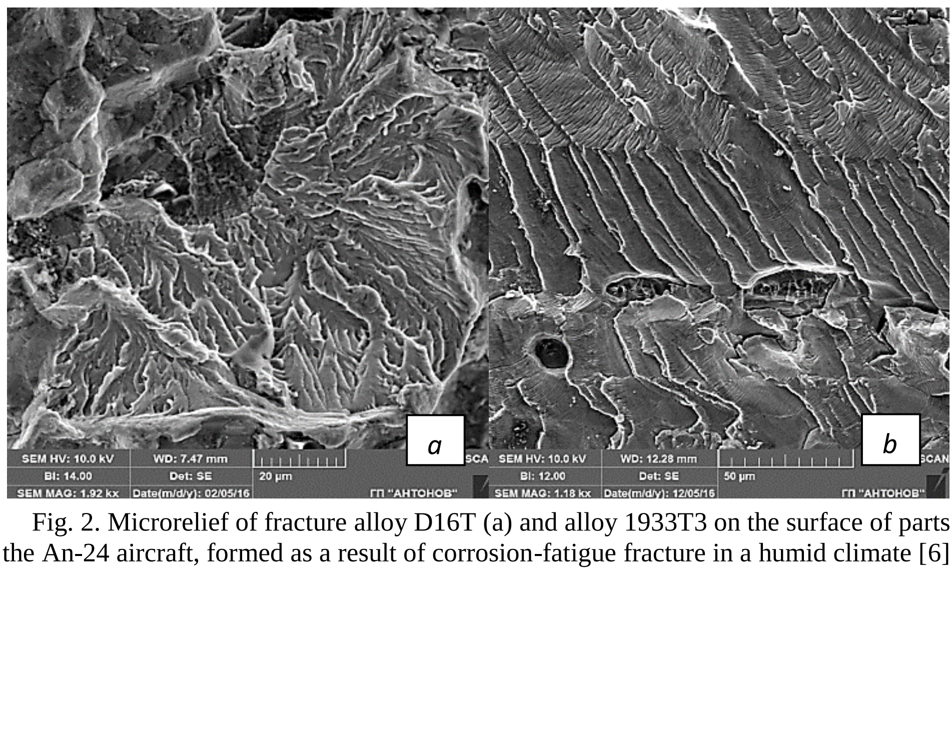

Fig. 2. Microrelief of fracture alloy D16T (a) and alloy 1933T3 on the surface of parts of the An-24 aircraft, formed as a result of corrosion-fatigue fracture in a humid climate [6].

The vibration factor, which is inherent in all aviation equipment, only increases and accelerates the corrosive effect on the power elements of aircraft [7]. Thus, taking into account the catastrophic damage of corrosion runoff to the aircraft structure, for a complete understanding of the contact of composite materials with titanium and aluminum alloys under vibration loading, it is necessary to conduct research in aggressive environments.

The purpose of the work is to determine the damage of the contact of aluminum and titanium materials with CFRP composite material under the action of vibration loads in corrosive and aggressive environments.

Testing procedure. The study of the influence of aggressive and corrosive environments on the contact of composite materials with aviation materials (Al, Ti) was carried out with the assistance and within the framework of the contract No 2025/88/UA between LLC Airlines «KCEHA» and the State University «Kyiv Aviation Institute».

The test conditions were to simulate the use of aircraft over the sea and ocean surface when using Antonov Ан-32П aircraft to extinguish fires with the intake of salt water from the Mediterranean Sea, as well as basing sites on the African continent near the oceans in a tropical climate with salty sea air.

Analysis has shown that, as a rule, seawater consists of a solution containing 95-96.5 % water and 3.5-5 % salts. The main component of these salts is sodium chloride (NaCl), which accounts for about 85 % of the total amount of dissolved salts. The remaining 15 % is accounted for by other salts and minerals, such as magnesium sulfate, calcium and potassium. Normal seawater contains the salts NaCl, $MgCl_2$, Na_2SO_4, $CaCl_2$, KCl, $NaHCO_3$, KBr, H_3BO_4, SCl_2, NaF, which are taken in a certain proportion. In general, 99.99 % of the salt composition of seawater is accounted for by these ions.

Analyzing the ASTM standards for testing materials in a corrosive environment, we can focus on testing in a 5% NaCl salt solution in water. It is the ASTM B117 standard that offers such a test in salt fog. But this standard is not the only one for testing in a corrosive environment. If materials that are more resistant to corrosion are used (titanium and composite materials), then other more aggressive standards are used that also include testing in alkaline environments. Standards such as ISO 9227, JIS Z 2371 and ASTM G85 offer more aggressive testing conditions compared to ASTM B117. So, since in our case we are interested in the contact of titanium alloys with composite materials, it is advisable to also use research in an elevated pH environment - an alkaline environment. The ASTM D543 standard specifically includes testing the resistance of plastics to chemical (alkaline) reagents.

Alkaline environments can occur inside aircraft structures operating near the coasts of seas and oceans for several reasons.

Firstly, minerals such as carbonates, silicates, oxides and hydroxides of alkali and alkaline earth metals (Na^+, K^+, Ca^{2+}, Mg^{2+}) get into the aircraft structure along with sea air, dissolve and release alkali ions into the water. This process, known as leaching, increases the content of hydroxide ions (OH^-) in the solution, which contributes to an increase in pH and the transformation of water into an alkaline solution.

Secondly, in arid climatic conditions with intense evaporation, water loses part of the solvent, and the remaining alkaline salts (for example, carbonates and bicarbontes) are concentrated. As a result, certain areas are formed in aircraft structures with a high content of alkaline components, in which pH can reach values of the order of 9-11 [4, 8].

And thirdly, microorganisms that live in such places on aircraft change the pH value due to waste products.

So, the following conditions for conducting research were determined for testing the influence of aggressive environments on the contact of composite materials with aviation materials:

1. Environments: air, 5% NaCl solution in water and alkaline KOH solution with a pH value of 11.
2. Test temperature 20-25 ºC.
3. Amplitude of mutual movement of samples 125 μm.
4. Load 6 MPa.
5. Oscillation frequency 30 Hz.
6. Test base 300 thousand cycles.
7. Sample materials: D16T and Ti6Al4V with CFRP.

The samples were made standard without surface treatment. The counter sample was metal, onto which the corresponding composite material processed on lathes and grinding machines was glued. Wear was determined using a vertical optimeter by taking readings from eight equivalent areas according to the method [9].

Analysis of the results of tests on the wear resistance of aviation materials in aggressive environments under vibration conditions. The test results are presented in Fig. 3. Analyzing the test results of aviation materials in combination with CFRP composite material made of carbon fiber in corrosive environments, it can be stated that the D16T alloy is very sensitive to changes in the environment. When tested in NaCl solution, its wear increased by 1.4 times, despite the fact that the wear resistance tests were carried out in an aqueous solution. The more resistant titanium alloy Ti6Al4V did not react at all to the salty environment. On the contrary, the wear of the titanium sample decreased due to the presence of water and a humid environment in the friction zone, which lubricated the friction surfaces in some places. The low test temperatures of 20 ºC did not allow the processes of hydrogenation of the titanium alloy surface to occur, and as a result, we record a decrease in wear by 1.09 times compared to the study in air.

Saltwater wear of D16T material is a complex phenomenon that combines chemical corrosion and mechanical abrasion, often called three-component or combined corrosion. In a saltwater environment, chlorine ions play a key role, provoking localized corrosion processes (pitting), which leads to a violation of the integrity of protective films on the surface of the material. Mechanical loads caused by vibration additionally accelerate the destruction process, since the worn surface becomes even more susceptible to the aggressive effects of salts. Titanium alloys are much more resistant to the marine environment, as evidenced by the test results.

When testing aviation materials in an alkaline KOH solution, the situation is somewhat different: the high pH value actively affects D16T and Ti6Al4V materials, sometimes leading to the destruction of passivating oxide films that naturally form on the materials. In the presence of abrasive particles formed during friction and additional mechanical abrasion, this protection is destroyed, which in turn accelerates the degradation processes of materials. Catastrophic failure of the D16T alloy shows chemical degradation and dissolution in an alkaline environment, which increases the wear of the material by more than 4 times.

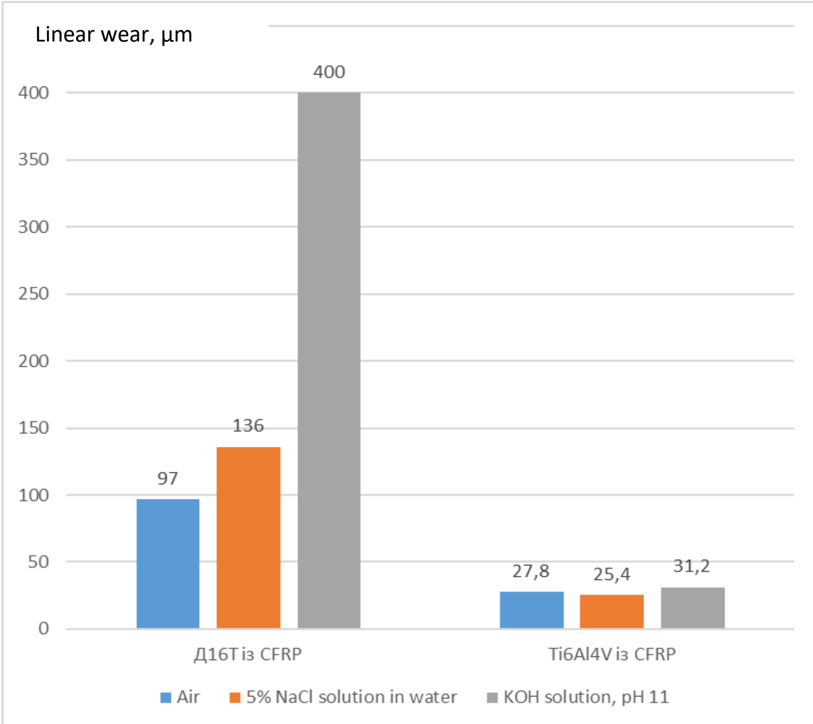

Fig. 3. Linear wear of aviation materials with carbon fiber CFRP depending on the corrosive environment during vibration tests.

When aluminum interacts with alkali, the following reaction occurs: aluminum dissolves in an aqueous solution of alkali with the formation of complex salts, for example, tetrahydroxoaluminate (with a lack of alkali) or hexahydroxoaluminate (with an excess of alkali), and the release of hydrogen [10]. The general reaction of the destruction of an aluminum alloy in an alkaline KOH solution can be written as follows:

$$2Al + 2KOH + 6H_2O = 2K[Al(OH)_4] + 3H_2\uparrow.$$

Due to the formation of alkaline environments and catastrophic destruction of aluminum-based alloys in aircraft power elements and increase the frequency of maintenance [2]. Particular attention is paid to the so-called tribocorrosion [11], where mechanical vibration loads and aggressive chemical effects of the environment act simultaneously. Such a synergistic effect requires engineers and materials a special approach when choosing structural materials and protective coatings. Often used methods of anodizing, chrome plating or applying special polymer layers, as well as the use of alloys (titaniums and composite materials) with increased corrosion resistance to minimize the total volume in such environments.

Titanium alloy Ti6Al4V has high corrosion resistance in many environments, including dilute alkali solutions. This is due to the formation of a strong oxide film on the titanium surface, which protects the metal from further interaction with the alkaline environment, as evidenced by the wear results that increased by 1.12 times. Although titanium alloys are resistant to most alkalis, one should take into account the concentration, temperature and presence of fluoride ions in the solution. For example, an increase in temperature by 10-15 ºC increases the chemical reaction by 2 times. An important factor influencing the Ti6Al4V alloy is the chemical composition of the environment and the duration of its action. Thus, in work [12], the authors, conducting a study of the influence of a corrosive environment on titanium alloys, established the processes of destruction of surface films of the VT6 titanium alloy after prolonged exposure to an aggressive environment, even a 3.5% NaCl solution (Fig. 4).

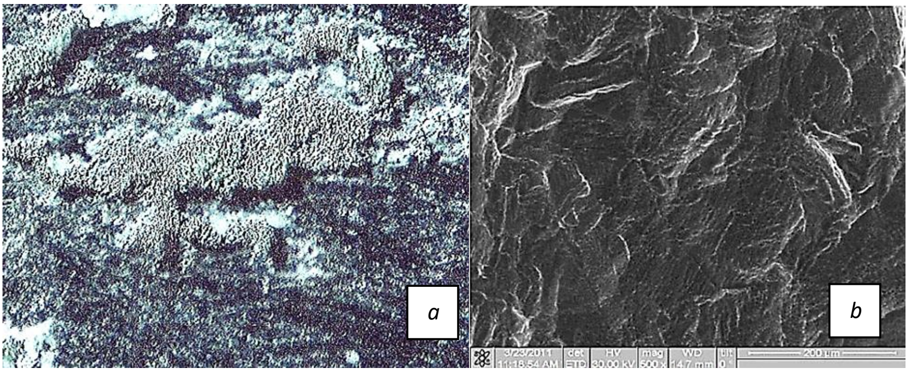

Fig. 4. Topographies of the surfaces of the VT6 alloy after corrosion in a 3.5% NaCl solution under anodic polarization conditions at 1.5 V (a) (x10) and the microstructure of the alloy fractures in an alkaline solution after 25 days (b) [12].

Regarding the influence of the corrosive environment on composite materials, the scenarios may be different. When using GFRP material with glass fibers and an epoxy matrix in alkaline environments, the reaction does not occur at all. That is, the friction process can occur without affecting the glass fiber. However, when using the CFRP composite material with carbon fiber, the aggressive effect of the corrosive environment can affect only the carbon reinforced fibers themselves with their destruction. This primarily depends on the type of fiber and the chemical composition of the environment. When Al-CFRP was in contact with a 3.5% NaCl solution under vibration loading conditions, the corrosive environment did not affect the CFRP at all, on the contrary, when Ti-CFRP was in contact, the friction surfaces were lubricated with water. When tested in an alkaline KOH environment, the situation did not change. The reason here may be either insufficient temperature or a short duration of the tests or the chemical environment.

However, in [13] the authors claim that with prolonged exposure to high concentrations of alkalis (sodium or potassium hydroxide) on carbon fiber, the so-called alkaline hydrolysis can occur. This is a process in which alkali interacts with the surface of the fiber, destroying its structure and reducing mechanical strength. Increasing the temperature significantly accelerates the process of alkaline hydrolysis. At high temperatures (90-100 ºC), even weak alkaline solutions can negatively affect carbon fiber. Summarizing the analysis of the influence of the corrosive environment on carbon fiber, we can say that although carbon fiber is resistant to alkalis in most cases, it is necessary to take into account possible negative consequences when working in conditions of high concentrations and temperatures, especially in elements of aircraft power structures, where high material strength is required.

Conclusions. Thus, the conducted tests of the influence of the corrosive environment on the wear resistance of aviation lightweight materials show us the absolute advantage of titanium alloys over aluminum alloys when used in nominally fixed joints of aircraft power structures with composite materials under vibration loads [14, 15]. The high resistance of the Ti-CFRP contact to the marine and humid climate ensures reliable and long-term use of aircraft structures while maintaining the periodicity of maintenance. At the same time, the contacts of Al-CFRP materials in the marine climate and alkaline solution environment show a sharp increase in the wear of aluminum materials, up to catastrophic wear and destruction of aircraft structural elements. This is evidenced by the increase in the frequency of maintenance for Antonov family aircraft and the use of a number of means to slow down and prevent the corrosive escape of the environment onto the aircraft structure.

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ВПЛИВ КОРОЗІЙНОГО ТА АГРЕСИВНОГО СЕРЕДОВИЩ НА КОНТАКТ АЛЮМІНІЄВИХ ТА ТИТАНОВИХ СПЛАВІВ ІЗ CFRP В УМОВАХ ВІБРАЦІЙНОГО НАВАНТАЖЕННЯ

Корозійні та агресивні середовища які виникають на поверхнях повітряних суден, що експлуатуються біля узбережжя морів та океанів негативно впливає на ресурс планеру та особливо на деталі силової конструкції елементів літака які знаходяться в умовно нерухомому контакті та мають вплив вібраційних навантажень під час польоту. В роботі представлено аналіз пошкоджень деталей на літаках Антонов які працюють біля океанів.

Представлено дослідження впливу корозійного середовища морської води та агресивного лужного середовища на контакт алюмінієвого сплаву Д16Т та титанового сплаву Ti6Al4V в парі із композиційним матеріалом CFRP під дією вібраційного фактору. Встановлено катастрофічне руйнування контакту Al-CFRP в умовах лужного середовища KOH із pH 11. Результати порівнюються із подібними дослідами без агресивних середовищ. Визначено, що сплав Д16Т дуже чутливий до зміни середовища. При випробуваннях в розчині NaCl його знос збільшився в 1,4 рази. Більш стійкіший титановий сплав Ti6Al4V взагалі не зреагував на солоне середовище. Навпаки, знос титанового зразка зменшився завдяки наявності води та вологого середовища в зоні тертя, що в деяких місцях змащувало поверхні тертя. Невеликі температури випробувань в 20 ºC не дозволяли відбуватись процесам наводнення поверхні титанового сплаву і в результаті ми фіксуємо зменшення зносу в 1,09 рази в порівнянні з дослідженням на повітрі.

Встановлено, що зношування в солоній воді матеріалу Д16Т є складним явищем, що поєднує хімічну корозію і механічне стирання, що часто називають трикомпонентною або комбінованою корозією. У середовищі солоної води ключову роль відіграють іони хлору, що провокують локалізовані процеси корозії (піттингу), що призводить до порушення цілісності захисних плівок на поверхні матеріалу. Механічні навантаження, зумовлені вібрацією додатково прискорюють процес руйнування, оскільки зношена поверхня стає ще сприйнятливішою до агресивного впливу солей. Титанові сплаві є набагато стійкішими до морського середовища.

Визначено що, високе значення pH активно впливає на матеріали Д16Т та Ti6Al4V, іноді призводячи до руйнування пасивуючих оксидних плівок, які, природним чином формуються на матеріалах. За наявності абразивних частинок які утворюються під час тертя та додаткового механічного стирання, цей захист руйнується, що у свою чергу прискорює процеси деградації матеріалів. Катастрофічне руйнування сплаву Д16Т показує хімічну деградацію та розчинення в лужному середовищі, що збільшує знос матеріалу більше чим в 4 рази.

Ключові слова: *вібрація, умовно нерухомий контакт, Д16Т, титановий сплав, знос, вуглецеве волокно CFRP, пошкодження, аналіз, агресивні середовища, корозія*.

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