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DAMAGE ANALYSIS OF TI-CFRP CONTACT ON BOEING 787 DREAMLINER SERIES AIRCRAFT IN NOMINALLY FIXED CONNECTIONS

The problems of operation of Boeing 787 Dreamliner aircraft since 2010 are analyzed. The introduction of a new design philosophy and the use of more than 50% composite materials in the structure have led to the emergence of new engineering challenges associated with the contacts of the Ti–CFRP system under vibration and operational loads. The work analyzes the zones of location and interaction of composite materials with titanium and aluminum alloys. It is established that designers strive to avoid Al–CFRP contacts as much as possible due to the high risk of galvanic corrosion and catastrophic failure of aluminum elements. Examples of damage and failure of titanium parts in nominally fixed joints that arise under the influence of vibrations or violations of aircraft production and assembly technology are presented. Technological methods of protection, reduction of destruction intensity and prevention of wear of parts surfaces are analyzed. It has been established that problems of Ti–CFRP contacts in fixed joints are characteristic mainly for new generation aircraft, which are just beginning to be mass-produced in the world. In the future, these problems may become a significant factor, requiring engineers to strengthen technical control of joint areas or implement new technological solutions to prevent them.

Key words: *aircraft, defects, composite materials, titanium alloys, fretting corrosion, vibrations, analysis, cracks, wear resistance.*

Introduction. The Boeing 787 Dreamliner is a family of wide-body twin-engine jet aircraft developed by Boeing to replace the 767 for long-haul flights [1]. It is the first completely new aircraft in the company since the release of the Boeing 777, characterized by high fuel efficiency, increased comfort and extensive use of composite materials. The use of more than 50 % composite materials [2] in the aircraft allows to significantly improve flight and tactical characteristics. Depending on the modification, the number of passengers accommodated in the cabin ranges from 242 to 350 seats. The aircraft consumes 20-25 % less fuel with a flight range of up to 16 thousand km.

Thanks to the use of carbon fiber reinforced plastic (CFRP) in the structural power elements of the aircraft, the cabin maintains increased humidity (15-25 % compared to classic Boeing 737 aircraft where humidity does not exceed 4-10 %) and pressure (equivalent to 1800-2000 meters compared to 2400 m) for passenger comfort during long flights. The fuselage of the aircraft has enlarged windows, and the design of the engines and the use of CFRP reduces the noise level in the cabin by 15-20 % during flight and by 60 % during landing, takeoff and taxiing at airports [3].

The Boeing 787 Dreamliner series includes the following modifications: Boeing 787-8 with a length of 56.7 m, up to 250 passengers and a flight range of up to 15700 km; Boeing 787-9 with a length of 63 m, 290 passengers and a flight range of up to 16300 km and Boeing 787-10 with a length of 69 m, up to 350 passengers and a flight range of up to 15700 km [4]. All these modifications are manufactured using more than

50 % composite materials, which is a new generation of aircraft. This is the first aircraft in the world built on solid sections of CFRP, unlike the Airbus 350 XWB aircraft, which is made on a metal frame with a composite content of 52-53 % [5] and which is its direct competitor.

Along with the widespread use of CFRP in the construction of new-generation aircraft, other metal materials are also used in the amount of: 20 % Ti, 15 % Al, 10 % steel and 5 % other materials. CFRP-metal contact in such aircraft is found in large numbers. Under conditions of vibration and operational loads from the operation of gas turbine engines and onboard equipment on the aircraft, damage occurs at the contact points as a result of microdisplacements, which are classified as fretting-corrosion [6] destruction.

The purpose of the work is to analyze damage to Ti-CFRP contact points under fretting conditions on 787 Dreamliner aircraft during maintenance and repair.

Problems with the Boeing 787 Dreamliner series aircraft. Since the Boeing 787 Dreamliner and Airbus 350 XWB series aircraft are aircraft of a new design and a new philosophy of using and applying composite materials, since the moment of their commissioning in 2011, this type of aircraft has always faced a number of problems.

The new design and new type of General Electric GEnx and Rolls-Royce Trent 1000 aircraft engines that have been in operation for many years have constantly faced technical problems. Damage to turbine blades, fuel supply problems and disruption of the gas turbine engine operating cycle have constantly led to flight restrictions and required large-scale maintenance programs and inspections of problem areas.

In the first years of operation (especially in 2013), the aircraft, which at that time numbered about 100 worldwide, had problems with overheating and ignition of lithium-ion batteries, which in the future required a total revision of the battery design and the introduction of special protective casings. For this reason, several events apparently occurred. For example, Boeing 787 airline «Air India», flying from Ahmedabad to Gatwick Airport in London, flight AI171, crashed three minutes after takeoff into a dormitory of a medical institution in India due to a battery fire [7]. There were 242 people on board. This is the first incident of an aircraft of this class with the loss of its fuselage since its introduction into service.

However, the main problem of the Boeing 787 Dreamliner is the defects in the assembly and fastening of the power structures and elements of the aircraft [8]. Since this aircraft has more than half of the parts made of CFRP, which are made of a modular block, the moment of docking and contact of these modules with each other and with other metal parts is quite responsible. The claims of engineers that the fuselage sections on some 787 models were connected and tightened incorrectly became one of the biggest problems. During the inspection, it turned out that hundreds (in some places even more than 900) of incorrectly installed fasteners (which were made of titanium alloy) were used during the assembly, and there were also problems with the tightening of parts. Such defects, as experts feared, could accelerate the wear of the fuselage in flight. Because of these quality control violations, Boeing repeatedly suspended the supply of new aircraft for inspections and elimination of deficiencies.

Due to problems with the contact of CFRP/GFRP composite materials with metal parts and fasteners, several incidents have occurred over the past 8 years [9]. For example, in March 2024, a Boeing 787-9 aircraft of the airline "LATAM Airlines", which was flying from Sydney to Auckland, began to descend from the flight level due to structural failure. The aircraft managed to land safely. Then 50 passengers were

injured, and 12 people were hospitalized. In August 2024, an aircraft of the same type "Qantas airline" suffered damage to the chassis due to the destruction of power elements during landing in Perth. The aircraft was taken out of service for repairs. In November, a Boeing 787-9 aircraft encountered severe turbulence during flight, resulting in structural failure, and in January 2025, an Etihad Airways Boeing 787-9 Dreamliner was forced to abort a takeoff from Melbourne due to problems with the mounting of a gas turbine engine.

Analysis of damage to contact Ti-CFRP. The massive contact of composite materials with metals on Boeing 787-9 Dreamliner class aircraft is the result of technological progress in the use of carbon-fiber plastics in an amount of 50 % or more. Modern technologies for the production of aircraft structures provide the possibility of forming the fuselage of the Boeing 787 Dreamliner in the form of monolithic sections with a diameter of up to 7.3 m and a length of up to 23 m. The rejection of traditional aluminum panels with numerous rivets became possible thanks to the use of large-sized autoclave furnaces, in which thermal curing of composite materials is carried out. Automated fiber placement (AFP) systems play a key role in this process, ensuring the precise location of CFRP strands without breaks, especially in the production of wings. This increases the homogeneity of the material and its operational reliability [10]. The use of such technologies allows: to increase the resistance of the structure to corrosion and fatigue damage by approximately 30%, to increase aerodynamic efficiency due to improved aircraft resistance to turbulence, and to create conditions for passenger comfort during long flights.

Along with CFRP, the aircraft also uses titanium and aluminum alloy materials, which are used on the Boeing 787 Dreamliner in approximately equal amounts of 15-20 %. However, the CFRP-Al contact has certain problems [11, 12] on aircraft, the main one being galvanic [13]. Carbon composite materials are excellent conductors, and aluminum is an active anode that forms a “galvanic couple” in the presence of an electrolyte (moisture or condensate). The potential difference between aluminum and carbon fiber can reach 0.5-1.0 V, which makes aluminum a “sacrificial” metal. If CFRP-Al contact occurs, aluminum dissolves as a result of a chemical reaction or is covered with a thick layer of loose aluminum hydroxide $Al(OH)_3$, which leads to dangerous corrosion. As a result, aluminum quickly collapses, losing strength.

According to regulatory documents: AMM (Aircraft Maintenance Manual), CSM (Corrosion Prevention and Control Manual), MIL Specs including MIL-STD-889 (dissimilar metal selection) and MIL-F-7179 (coating), FAA Advisory Circulars (documents AC 43-4B and AC 43-206 describe general methods for detecting and treating aircraft corrosion) and works [14], the level of galvanic activity significantly depends on the area of the CFRP-Al contact. Because of this, at the design stage of aircraft, engineers carefully calculate the ratio of the anode and cathode areas, avoiding large open arrays of CFRP directly next to thin aluminum elements or using Ti and GFRP as intermediate materials. Thus, the Ti-CFRP contact on aircraft is the most massive among other possible material contacts.

The use of titanium alloy is increasing with the improvement of aircraft design and performance. Titanium alloys Ti6Al4V and Ti10V2Fe3Al have been used in key parts of aircraft, such as the horizontal tail joint (shaft). The use of these two titanium alloys increases the service life of large transport aircraft to 60 thousand flight hours or more [15]. In Europe, the Airbus A380 was the first aircraft with an all-titanium pylon, which is used in the A350.

Titanium alloy fasteners (bolts and rivets) significantly reduce the weight of modern aircraft (Fig. 1), not only improving flight performance, but also reducing the cost of operating the aircraft by reducing fuel consumption. About 200 thousand titanium alloy fasteners are required for each Boeing 787 Dreamliner aircraft. The potential for the development of titanium alloy fasteners for aviation is enormous. To accelerate the industrialization of civil and military airliners, the coming years will be a period for the development of titanium and composite materials in the aviation industry.



Fig. 1. Fasteners made of titanium alloys (*a*) used in aircraft for contact with composite materials (*b*).

The high use of CFRP in aircraft creates the problem of contact of the composite material with other components and structures [16, 17], and titanium alloys are the most suitable for this. Due to similar coefficients of thermal expansion [18] and the resistance of titanium to corrosion and fracture [19], this contact pair is found in thousands of places in the aircraft. In the fuselage structures of the Boeing 787 Dreamliner, these are the places of contact of the fuselage with metal nodes. In the wings, these are the places of attachment to the center section, as well as the use of titanium spars and fittings to ensure strength during high maneuvers (Fig. 2). In the landing gear, these are the places of installation of supports, where stress concentration from aircraft landings occurs and contact with Ti-CFRP laminates and panels. However, the most massive contact is the bolted joints and various fastening interfaces, which are almost 100% made of titanium. The use of titanium in combination with CFRP is a key engineering technique for the Boeing 787 Dreamliner (Fig. 3). It allows for strong and durable components, eliminating corrosion and ensuring operational reliability, while significantly reducing the weight of the structure.

However, the use of Ti-CFRP contacts creates a certain problem [20] for the aircraft. Vibrations from the operation of gas turbine engines and onboard equipment during flights lead to loosening of connections (usually bolted) and micro-mixing of contacting connections is formed, which leads to damage as a result of fretting corrosion [21, 22]. Even 1-5 μm is enough to implement mechanisms that are characteristic for the formation of seizure points and surface failure with the appearance of microcracks. The formation of cracks on the surfaces is associated with the mechanical movement of connections and delamination of laminate structures [23] during cyclic loads with subsequent mechanical mixing of these structural layers.

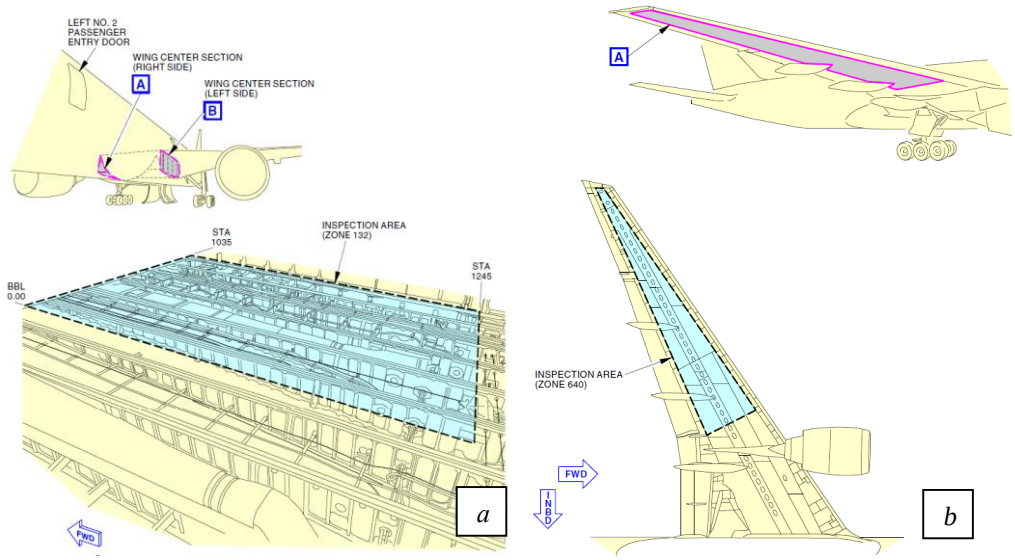


Fig. 2. Contact points of Ti-CFRP with the center section (*a*) and wing panels (*b*) in the Boeing 787 Dreamliner aircraft.

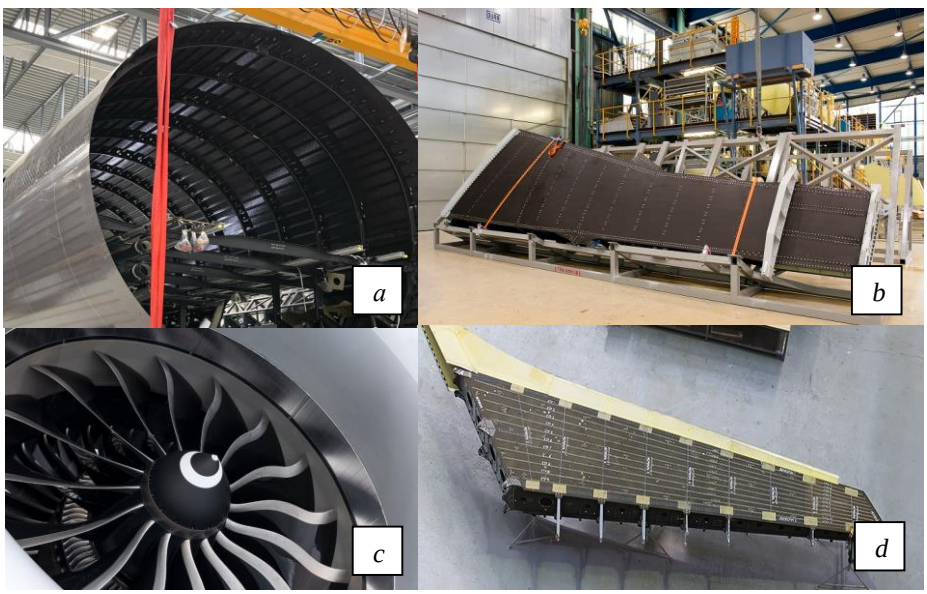


Fig. 3. Use of CFRP in aircraft elements: a – fuselage, b – wing elements, c – engine blades, d – tail.

Laminates used on Boeing 787 Dreamliner aircraft are typically composed of Ti-CFRP material combinations and are classified as TiGr-type metal-fiber laminates. These are advanced hybrid composite materials in aircraft construction, consisting of directionally oriented thin layers of Ti with a thickness of 0.3 mm and CFRP. They combine the best mechanical and physical properties of metals and high-modulus polymers and have the following advantages [23]:

1. Exceptional specific strength and stiffness. The material has strength at the level of steel, but much less weight, which allows to significantly lighten the aircraft structure and reduce fuel consumption.

2. Elimination of galvanic corrosion. Direct contact of Al-CFRP alloys causes severe electrochemical corrosion, which was described above. Titanium has an electrochemical potential close to CFRP, so Ti-CFRP laminates are completely free from this problem.

3. Fatigue resistance and crack retardation. The metal-fiber structure absorbs energy perfectly. If a microcrack appears in the titanium layer, the carbon fibers of the adjacent layer redistribute the load onto themselves, slowing down or stopping its propagation (microstructural bridge effect).

4. High thermal resistance. Thanks to the combination of titanium and polyimide, such laminates are able to work effectively in high temperature conditions (over 150-200 °C), which is not available for classic Al-GFRP laminates (GLARE).

5. Close coefficients of thermal expansion. Titanium and carbon fiber expand almost equally when heated, which minimizes internal residual stresses during sharp temperature fluctuations at altitude during flight.

The main problems of Ti-CFRP laminates in aircraft are related to their mechanical processing by cutting, degradation of adhesive joints in a humid and warm environment during loads and vibrations [24], as well as fatigue damage when fixing bolted joints. This limits durability and requires special technologies for processing and controlling the surface of the joints. The biggest problem is fatigue damage in mechanical adhesive joints of the Ti-CFRP system, as it leads to the formation of microcracks and, in turn, causes structural failure and loss of structural strength.

Figure 4.a shows the failure of the TorayT800/3900 hybrid laminate (part number BAC5317-2) which is used in the wing-fuselage joints on the Boeing 787 Dreamliner. These are high-strength laminates with a 350 °F approved prepreg manufactured by Toray Industries (Japan) and manufactured to Boeing BMS8-276 standards, which is used for materials used in fuselages, wings and tails. During vibration and flight loads, delamination of the TorayT800/3900CFRP+Ti6Al4V laminate system occurs with the formation of slippage and the formation of cracks characteristic of fretting corrosion.

In case of problems with bolt fixing (loosening, surface damage, looseness or tightness, distortions, unprepared surface of bolted or carbon fiber parts, violation of assembly technologies, etc.) of TiGr or CFRP laminate structures, during micro-movements, titanium alloy adhesion and a harder and abrasive surface of carbon fiber are formed with subsequent smearing of titanium alloy on the surface of carbon fiber. As a result, Ti-Ti contact is formed with fretting corrosion damage and the formation of cracks in the surfaces of titanium alloy parts. Figure 4 shows the surfaces of damage to titanium parts (bolts and inserts) of Boeing 787 Dreamliner aircraft according to specifications BAC5004-2, BAC5063-4 in contact with CFRP during vibration loads.

Problems associated with the contact of titanium alloys and composite materials are described in a number of works [25-31]. The authors [25] note the high wear of titanium alloys (up to 10 times greater) than CFRP or GFRP, which is associated with the peculiarities of the physical, mechanical and chemical properties of titanium alloys and their structure. High adhesive wear, low surface strength, poor thermal conductivity and chemical activity of titanium alloys lead to the fact that titanium alloys have poor antifriction properties without special coatings and modifications. However, its use is only increasing in the production of aircraft and in contact with composite materials

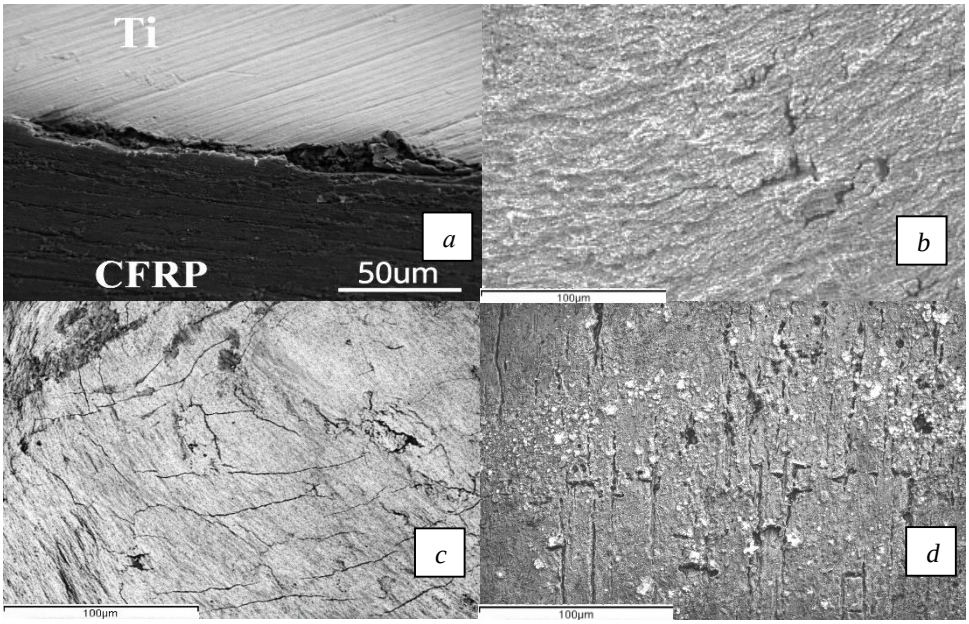


Fig. 4. Damage at the Ti-CFRP contact on parts of the Boeing 787 Dreamliner series aircraft:

a – delamination and damage to the hybrid laminate of the TorayT800/3900CFRP+Ti6Al4V system at the fuselage and wing contact;

b – topography of damage to a titanium bolt (BAC5004-2 with anodized coating BAC5034-1) under vibration loads;

c – characteristic relief damage by fretting corrosion of bolts of specifications: BACB30US (general purpose bolts for composite materials), BACB30V (high strength bolts for fuselage and wings), BACB30X (bolts with anodized coating for protection against galvanic corrosion), BACB30Y (bolts with dry Teflon grease for contact with CFRP), BACB30Z (bolts with sealed paint coating for wet areas of the chassis and wing) made of titanium alloy Ti-6Al-4V under vibration loads in contact with CFRP on aircraft;

d – characteristic fretting damage of parts made of titanium alloys of specifications: BACB31 (sleeves and inserts), BACR15CE (rivets for CFRP panels), BACN10Y (self-locking nuts).

Due to damage to titanium alloy parts in aircraft, while maintaining the required level of aviation reliability and flight safety, engineers are forced to increase maintenance costs or limit the service life of such joints. Works [26, 27] show that titanium parts and fasteners can be quite successfully covered with protective coatings or technological methods of surface treatment. Such methods include: surface plastic deformation, chemical-thermal treatment, electrospark alloying, etc. There are many works that increase the wear resistance of titanium parts by these methods in contact with steels, but there are practically no works on studying the influence of technological methods of increasing the wear resistance of titanium with composite materials.

One of the technological techniques used in production is the use of intermediate or sacrificial materials [28]. In works [29, 30], the effective use of wear-resistant polymer composite materials and plastic metals that minimize damage to the Ti-CFRP contact is shown. Also, one of the effective ways to protect titanium parts is the use of ceramic coatings applied by gas-thermal methods. In works [31-33], the authors demonstrate the successful increase in the wear resistance of titanium alloys by plasma

coatings. However, such total protection of metal parts can shift the destruction of the Ti-CFRP contact towards the destruction of composite materials. The contact is no longer Ti-Ti, but ceramic coatings and composite materials. Considering that ceramic coatings can have a hardness of up to 2 GPa, the destruction of the contact pair will change significantly.

Conclusions. Thus, the analysis of damage to parts on the Boeing 787 Dreamliner aircraft shows that Ti-CFRP contacts have been encountered en masse since the introduction of new generation aircraft and a new design philosophy in 2010. There are thousands of such places on the B787 and A350XWB aircraft, which require designers to carefully approach the selection of materials and protection of the contact point. Many incidents that occurred with the Boeing 787 Dreamliner aircraft around the world were related precisely to the problem of titanium bolted joints in the Ti-CFRP contact, which were damaged as a result of vibration loads and violations of aircraft production technologies. Since in the future there will only be more such aircraft, the problem of contact of titanium alloys with composite materials during vibrations will only increase. Therefore, it is necessary to focus now on preventing and preventing problematic contact points by searching for new technological approaches to protecting the surfaces of aviation parts and engineering solutions that will minimize damage without additional maintenance operations with the necessary level of reliability and flight safety.

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АНАЛІЗ ПОШКОДЖЕНЬ КОНТАКТУ Ti-CFRP НА ЛІТАКАХ СЕРІЇ BOEING 787 DREAMLINER У НОМІНАЛЬНО НЕРУХОМИХ З'ЄДНАННЯХ

Проаналізовано проблеми літаків серії Boeing 787 Dreamliner за період їх експлуатації з 2010 років. Нова філософія будування та використання більше половини композиційних матеріалів в конструкціях подобних літаків приводять до того що виникають нові проблеми пов'язані із контактами Ti-CFRP в умовах вібраційних та експлуатаційних навантажень. В роботі представлено аналіз та проблеми місць розташування та контакту композиційних матеріалів та титанових і алюмінієвих сплавів. Встановлено що інженери та конструкторі максимально намагаються замінити або не допустити контакту Al-CFRP в наслідок гальванічної корозії та катастрофічного руйнування алюмінієвих деталей. В свою чергу контакт композитів із титаном максимально сприятлив для літаків хоча і не позбавлений суттєвих проблем.

Представлено пошкодження та руйнування які виникають на титанових деталях в контактах під час вібрацій або порушення технологій виробництва та збирання літаків. Виявлено руйнування характерні для фретинг-корозії із утворенням мікротріщин на поверхнях титанових деталей. Проаналізовано технологічні методи захисту, зменшення руйнування та запобігання зношування поверхонь деталей та контакту в цілому. Встановлено, що проблеми контакту Ti-CFRP в номінально нерухомих з'єднаннях притаманні масово лише літакам нових поколінь (Boeing 787 Dreamliner, A350XWB та ін.) які тільки починають масово експлуатуватися у всьому світі і в майбутньому стануть суттєвою проблемою. що вимагатиме від інженерів підвищеного технічного обслуговування місць з'єднання або застосування технологічних рішень для попередження цієї проблеми в майбутньому.

Ключові слова: *титанові сплави, покриття, зносостійкість, фретинг-корозія, скловолокно, аналіз, випробування, номінально нерухомий контакт.*

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