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CRITERIA FOR PERMISSIBLE FRETTING MODES IN TITANIUM ALLOY – POLYMER COMPOSITE JOINTS OF AVIATION EQUIPMENT

Анотація. *За фізико-статистичною моделлю фретинг-зношування титанових сплавів Ti6Al4V і Ti5Al5V5Mo1Cr1Fe у контакті з вуглепластиком і склопластиком виділено три зони режимів фретингу за амплітудою мікропереміщень. Визначено допустимі амплітуди мікропереміщень і контактні тиски з'єднань та запропоновано ознаки кожної зони, які можна виявити під час технічного обслуговування авіаційної техніки.*

Ключові слова: *титановий сплав, полімерний композит, фретинг, допустимий режим, технічне обслуговування.*

Annotation. *A physical-statistical model of fretting wear of Ti6Al4V and Ti5Al5V5Mo1Cr1Fe titanium alloys against carbon and glass fibre reinforced polymers is used to distinguish three zones of fretting modes by the micro-displacement amplitude. Permissible micro-displacement amplitudes and contact pressures of the joints are determined, and features of each zone that can be detected during maintenance of aviation equipment are proposed.*

Keywords: *titanium alloy, polymer composite, fretting, permissible mode, maintenance.*

Polymer composite materials (PCM) account for more than half of the structural mass of modern passenger aircraft and are widely used in military aviation equipment [1]. Composite parts are joined to titanium alloy fittings, which, unlike aluminium alloys, do not form a galvanic couple with carbon fibre reinforced polymer (CFRP). Engine vibration and aerodynamic loads cause cyclic micro-displacements of tens to hundreds of micrometres in these nominally fixed joints, resulting in fretting corrosion; the damaged areas become sites of fatigue crack nucleation [2]. Damage of this kind in titanium alloy-CFRP contacts has been found, in particular, in service on Boeing 787 aircraft [3].

Previous studies [4] showed that against a PCM a titanium alloy wears 6–20 times more than the composite itself, and that its wear depends non-linearly on the micro-displacement amplitude and the contact pressure. Neither the Archard law nor the energy wear law [5] with constant coefficients describes these data: the energy wear coefficient varies 7.8-fold. Maintenance therefore needs criteria linking the loading parameters to the damage mechanism and its visible features.

The aim of the work is to use a physical-statistical model of fretting wear to determine the zones of fretting modes, the permissible micro-displacement amplitudes and contact pressures of titanium alloy–PCM joints, and the features of these zones that can be used in maintenance.

The model is based on tests of Ti6Al4V and Ti5Al5V5Mo1Cr1Fe alloys against CFRP and glass fibre reinforced polymer (GFRP) in an annular flat-on-flat contact at a frequency of 30 Hz, a test base of $3\cdot10^5$ cycles, amplitudes of 50, 175 and 300 μm and pressures of 5, 15 and 25 MPa [4]. According to the plasticity index, titanium contacts carbon fibres elastically ($\psi = 0.50$) and glass fibres plastically ($\psi = 1.65$), hence the 1.5-2.5 times higher alloy wear against GFRP.

The friction surface is treated as a set of areas protected by an oxide film and a third-body layer and juvenile areas with adhesive Ti-Ti interaction, where the work of adhesion is 33-36 times higher. Failure of the protective layer along the slip path is described by weakest-link Weibull statistics [6], which gives the steady-state fraction of juvenile areas

$$n_j^* = 1 - \exp\left[-\left(\frac{\delta}{\delta_c}\right)^m\right] \quad (1)$$

where δ is the micro-displacement amplitude; $\delta_c \approx 210$ μm is the characteristic amplitude; $m = 4$ is the Weibull modulus. The linear wear of the alloy after N cycles

$$h = N\lambda_a\left[q_k \exp\left(\frac{P-P_0}{P^*}\right) + \frac{4K_k P\delta}{H} n_j^*\right] \quad (2)$$

consists of an oxidative-fatigue component, which, as in thermally activated failure models [7], grows exponentially with the pressure P (characteristic pressure $P^* = 11.8$ MPa, $P_0 = 5$ MPa), and an adhesive component acting only on juvenile areas. Here q_k is the wear per cycle at P_0 (0.068 and 0.158

nm/cycle for CFRP and GFRP); $K_k = (7.2…8.5)\cdot10^{-5}$ is the adhesive wear coefficient; H = 4.5 GPa is the alloy microhardness; λ_a is the alloy grade factor (1 for Ti6Al4V and 0.915 for Ti5Al5V5Mo1Cr1Fe). Against 36 measured wear values, the coefficient of determination is R^2 = 0.987 and the mean error is 7.9 %. The oxidative-fatigue component is 2.3 times larger against GFRP, in line with the plastic contact with glass fibres.

By equation (1), fretting modes fall into three zones (Fig. 1, a). In zone I (δ < 100 μm, δ/δ_c < 0.5) the fraction of juvenile areas does not exceed 0.05: at an amplitude of 50 μm n_j^* = 0.003, the wear is almost entirely oxidative-fatigue wear, and the friction surface is covered by a continuous oxide layer. In zone II (δ = 100…250 μm) n_j^* grows from 0.05 to 0.87, i.e. a mere 2.5-fold increase in amplitude strips the protective layer from most of the surface; at 175 μm (n_j^* = 0.38) the adhesive component accounts for 23-29 % of the wear against CFRP and 13-17 % against GFRP. In zone III (δ > 250 μm) the protective layer is practically destroyed (n_j^* = 0.985 at 300 μm), the adhesive component gives 56–64 % and 39-48 % of the wear, and seizure spots and titanium transferred to the composite are visible on the friction surface [4].

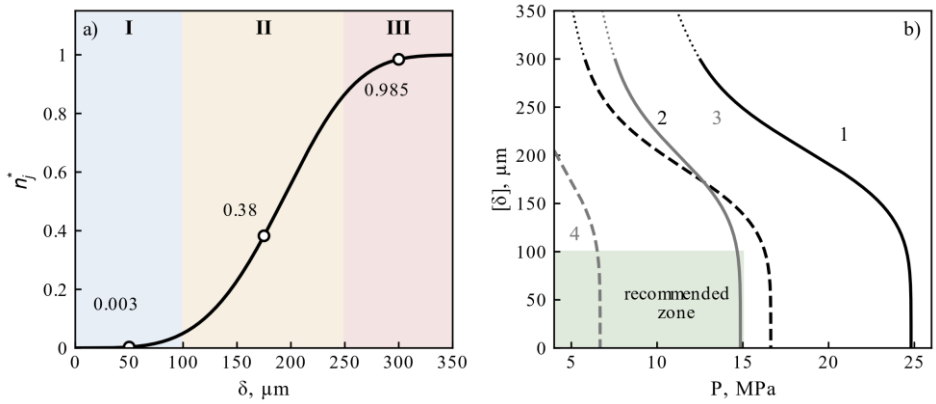


Fig. 1. Fraction of juvenile areas and fretting mode zones (a); permissible micro-displacement amplitude for Ti5Al5V5Mo1Cr1Fe after $3\cdot10^5$ cycles (b): 1, 2 – CFRP; 3, 4 – GFRP; 1, 3 – [h] = 100 μm; 2, 4 – [h] = 50 μm; dotted – extrapolation

Solving equation (2) for δ at a specified permissible wear [h] gives the permissible amplitude [δ] (Fig. 1, b). For the Ti5Al5V5Mo1Cr1Fe–CFRP pair at [h] = 100 μm after $3\cdot10^5$ cycles, [δ] ≈ 265 μm at 14 MPa and ≈ 190 μm at 20 MPa, while above 25 MPa the oxidative-fatigue component alone exhausts the permissible wear. For GFRP this limit drops to ≈ 15 MPa. Under the stricter requirement [h] = 50 μm, the limiting pressure is ≈ 17 MPa for CFRP and only ≈ 7 MPa for GFRP. Reducing the amplitude from 300 to 100 μm at 15 MPa lowers the calculated alloy wear 2.7 times against CFRP and 1.9 times against GFRP, and reducing the pressure from 15 to 5 MPa at δ = 100 μm lowers it 2.3 times for both composites.

The alloy wear hardly depends on temperature: at −50 °C the composite wear is 20-25 % lower than at +50 °C, while the alloy wear changes by no more than 3 % [8], since failure and recovery of the protective layer are thermally activated and compensate each other.

Zone features and maintenance actions are given in Table 1. Since vibration relaxes the preload of composite bolted joints [9], increasing the micro-displacements, preload checks should be combined with inspection of the contact surfaces.

Table 1 – Zones of fretting modes and maintenance actions

Zone	δ, μm	n_j^*	Features of the contact surface	Maintenance actions
I	< 100	< 0.05	continuous oxide layer and third-body layer of titanium oxides	inspection at scheduled intervals
II	100…250	0.05…0.87	mixed surface: oxides and areas of juvenile metal	restoring the bolt preload, shorter inspection interval
III	> 250	> 0.87	seizure spots, titanium transferred to the composite	repair or replacement of the part, protective coatings or interlayers

For joints that cannot be kept in zone I, the adhesive component should be reduced: it is inversely proportional to the hardness of the alloy surface, and conversion coatings and interlayers with a low work of adhesion to titanium reduce the coefficient K_k and increase δ_c [10], shifting the boundary of zone II towards larger amplitudes.

Conclusions. According to the physical-statistical model, fretting modes of titanium alloy-PCM joints fall into a zone of oxidative-fatigue wear ($\delta < 100$ μm), a transition zone (100…250 μm) and a zone of adhesive wear ($\delta > 250$ μm). At a permissible wear of 100 μm per $3 \cdot 10^5$ cycles, the limiting contact pressure for the Ti5Al5V5Mo1Cr1Fe alloy is ≈ 25 MPa against CFRP and ≈ 15 MPa against GFRP. In maintenance, micro-displacements should be limited to 100 μm and the pressure to 15 MPa; seizure spots on a titanium part and titanium transferred to the composite indicate zone III and call for repair or surface protection. 4. Within ±50 °C the alloy wear is practically independent of temperature, so these criteria can be applied without a temperature correction.

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