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TRIBOLOGICAL BEHAVIOR OF PVD AND ELECTROPLATED AIRCRAFT COATINGS

This paper investigates the tribological behavior in sliding friction and the wear resistance of cathodic vacuum-arc (PVD) and electroplated coatings deposited onto high-strength titanium alloy VT-22 and structural steel VKS-170. The relevance of the study is driven by the urgent need to replace environmentally hazardous hard chrome plating with vacuum-arc PVD alternatives, as well as to overcome the high tendency of titanium alloys toward adhesive seizure and galling in aerospace friction units. Face-sliding friction tests were conducted in an AMG-10 aviation hydraulic fluid medium against an AISI 1045 steel counterbody (45–50 HRC). The investigated surface systems included electroplated hard chromium, cathodic vacuum-arc coatings of hard chromium, soft chromium, and molybdenum, as well as uncoated base materials. The experimental findings demonstrate that electroplated chromium exhibits the lowest wear rate. Among the vacuum-arc deposits, hard chromium and molybdenum demonstrate high wear resistance on the VT-22 alloy, which, coupled with exceptional adhesion strength, positions them as viable, eco-friendly substitutes for galvanic chrome plating. Conversely, soft PVD chromium showed poor durability due to a porous columnar microstructure. Uncoated VT-22 suffered catastrophic adhesive seizure driven by localized microwelding and lubricant film breakdown. Additionally, a pronounced substrate (eggshell) effect was identified: the higher elastic compliance of VT-22 increased stress concentrations within thin functional layers, yielding 30–50% higher wear than on the stiffer VKS-170 steel. Practical recommendations are formulated for applying thick PVD coatings in aerospace pivot joints and plain bearings.

Key words: *titanium alloy VT-22, vacuum-arc PVD coatings, electroplated chromium, molybdenum coating, sliding wear, AMG-10 hydraulic fluid, adhesive wear, substrate effect*

Introduction. Support pivots, wing mechanization systems, and landing gears are among the most heavily loaded components in modern aircraft. Major aerospace manufacturers (Boeing, Airbus, Antonov State Enterprise) widely utilize high-strength titanium alloys – specifically VT-22 and counterparts such as Ti-10V-2Fe-3Al and Ti-5Al-5Mo-5V-3Cr – for structural brackets, trunnions, and plain bearing raceways. This structural choice achieves substantial airframe weight savings while retaining high specific strength, corrosion resistance, and fatigue endurance.

However, implementing titanium alloys in dynamic tribological assemblies is severely restricted by their poor wear resistance. Fundamental investigations [1 – 3] indicate that titanium possesses high chemical affinity for atmospheric gases and metallic counterbodies, a low strain-hardening exponent, and low thermal conductivity. During sliding, these characteristics cause localized flash temperatures at real contact areas, triggering rapid degradation of passivating TiO_2 films, severe adhesive galling, material transfer, and metallic tearing even under moderate contact pressures.

Historically, hard electroplated chromium served as the conventional protective coating, offering low friction, high microhardness, and adequate corrosion resistance. Nevertheless, galvanic plating faces stringent regulatory bans (REACH, EPA) due to toxic hexavalent chromium (Cr^{6+}) compounds and hazardous processing solutions.

Furthermore, evaluations by the Hard Chrome Alternative Team (HCAT) [4, 5] emphasize that electrodeposition induces severe hydrogen embrittlement, reducing fracture toughness and degrading the high-cycle fatigue strength of high-strength structural steels and titanium alloys by 30 – 50 %.

Cathodic vacuum-arc physical vapor deposition (Arc-PVD) with ion bombardment has emerged as an eco-friendly, high-performance alternative. The fundamental physics of vacuum-arc plasma streams [6 – 8] enables highly ionized metallic fluxes (70 – 90%) generated by cathodic spots in vacuum. Energetic ion bombardment and dynamic atomic mixing at the interface yield dense, non-porous coatings with superior substrate adhesion (up to 25 - 35 kgf/mm$_2$) and tailorable microhardness.

A critical challenge in titanium surface engineering is the "eggshell effect" [9, 10]. Because titanium exhibits a low elastic modulus ($E \approx 110 – 115$ GPa) compared to structural steel ($E \approx 200 – 210$ GPa), thin, superhard coatings flex elastoplastically under heavy contact loads, causing premature microcracking and spallation. Mitigating this requires optimizing deformation compatibility metrics, notably the ratios H/E (elastic strain to failure) and H^3/E^2 (resistance to plastic deformation) proposed by Leyland and Matthews [9].

In this context, ductile transition-metal films, particularly molybdenum-based systems, offer distinct advantages. During sliding, molybdenum undergoes tribochemical oxidation to form lubricious Magnéli phases (MoO_3, Mo_4O_{11}) that act as low-shear self-lubricating barriers, significantly curbing wear [11]. Complementary thermal diffusion saturation processes [12, 13] can further improve load capacity by creating hardened support sublayers beneath these functional films.

Comparative tribotests [14] confirmed that substituting galvanic chrome with vacuum-arc chromium and molybdenum coatings on VKS-170 steel and VT-22 alloy drastically reduces linear wear rates while preventing surface seizure. Studies on combined surface treatments [15] similarly established that molybdenum-containing oxynitride layers combine damping capacity with high localized hardness (up to 12 GPa), effectively relaxing peak contact stresses without brittle fracture.

The operating environment and lubricant condition also decisively govern coating reliability. As established in [16], aviation hydraulic fluids and oils subject to extreme temperature swings (-57 °C to (+50 °C) suffer from water emulsification and submicron ice formation, which disrupt boundary lubricant films and activate abrasive-corrosive wear, necessitating superior intrinsic seizure resistance under lubricant-starved conditions.

Further examining severe operating envelopes, investigations in [17] demonstrated that thick (70 μm) vacuum-arc molybdenum coatings on VT-22 withstand extreme contact pressures (20 and 30 MPa). Their enhanced damping capacity suppresses the "eggshell effect" and markedly extends operational endurance under cyclic micro-impact sliding.

Nonetheless, comprehensive quantitative sliding laws for surface-modified VT-22 in standard aviation AMG-10 fluid across varying contact pressures remain insufficiently established. In particular, systematically clarifying wear micromechanisms between electrolytic and vacuum-deposited architectures and defining the threshold conditions governing catastrophic thermofrictional seizure demand focused investigation.

The purpose of the study is to investigate sliding tribological regularities, quantitatively evaluate the wear resistance of electroplated and cathodic vacuum-arc Cr-

and Mo-based coatings on VT-22 titanium alloy and VKS-170 steel in AMG-10 hydraulic fluid at 6 and 9 MPa, determine the underlying physical wear mechanisms, and provide practical recommendations for their implementation in aircraft friction assemblies.

Testing procedure. The tribological sliding friction behaviour was experimentally investigated on a specialized testing rig designed for evaluating the tribotechnical parameters of face-sliding flat contact pairs under constant and adjustable velocities. The kinematic configuration of the rig enables simultaneous parallel loading of two independent friction pairs under identical velocity and force conditions, thereby completely eliminating the influence of temperature drift and random load fluctuations on the comparative results. A rotating ring-shaped counterbody makes contact along its annular end face with a stationary disk under a specified normal pressure. Operating conditions were achieved using a smooth run-in protocol involving gradual stepped loading up to the nominal contact pressure with concurrent spindle acceleration to a linear sliding velocity of v = 1.0 m/s [14].

Friction tests were conducted in a bath of AMG-10 aviation hydraulic fluid at two fixed levels of specific contact pressure: 6 MPa, representing typical contact stresses in wing mechanization hinges and pivot joints, and 9 MPa, simulating severe/forced operating regimes of the tribological assembly.

The specimens used for coating wear evaluation were rollers (50 mm in diameter) fabricated from two aerospace-grade structural materials:

- high-strength titanium alloy VT-22 in the heat-treated condition (quenched and aged to a hardness of 36 – 40 HRC);
- high-strength, medium-carbon, complex-alloyed structural steel VKS-170 (hardness 48 – 52 HRC).

In all experimental cycles, the counterbody was fabricated from structural quality carbon steel 45 (AISI 1045 equivalent) subjected to bulk heat treatment to a hardness of 45–50 HRC, ensuring the stability of the working surface microgeometry throughout testing.

The experimental matrix comprised four surface modification variants as well as uncoated baseline specimens of VT-22 and VKS-170:

- electroplated hard chromium deposited according to industrial specifications from a standard sulfuric acid chromium plating bath;
- cathodic vacuum-arc hard chromium deposited under a deposition regime with an increased negative bias potential and high ion current density, yielding a fine-grained, non-porous layer of elevated microhardness;
- cathodic vacuum-arc soft chromium formed under mild plasma conditions with a pronounced columnar crystallite orientation;
- cathodic vacuum-arc molybdenum produced by the condensation of a molybdenum plasma generated by vacuum cathodic arc spots.

The wear rate of the friction surfaces, I, was determined gravimetrically from the specimen mass loss using an analytical balance with a resolution of 0.1 mg, followed by recalculation of the mass loss per kilometre of sliding distance (mg/km).

Research findings and their analysis. Quantitative analysis of the obtained tribological data reveals a pronounced differentiation in wear resistance governed by the phase-structural state of the coatings, their mechanical properties, and the nature of the substrate.

At a specific contact pressure of 6 MPa, the lowest degradation rate was recorded for electroplated hard chromium: on both VKS-170 steel and VT-22 titanium alloy substrates, the wear rate was identical at 0.08 mg/km. Among the PVD coatings, cathodic vacuum-arc hard chromium demonstrated the best performance, exhibiting a wear rate of 0.12 mg/km on steel and 0.17 mg/km on the titanium substrate. The cathodic vacuum-arc molybdenum layer exhibited slightly higher values: 0.18 mg/km on steel and 0.24 mg/km on titanium. Cathodic vacuum-arc soft chromium displayed the lowest load-bearing capacity among the protective films, with wear rates reaching 0.30 mg/km on steel and 0.64 mg/km on titanium.

The performance of the uncoated base materials revealed a stark contrast between steel and titanium. Uncoated VKS-170 steel at 6 MPa wore at a rate of 0.32 mg/km, which is comparable to that of soft chromium (fig.1). In contrast, uncoated VT-22 titanium alloy suffered catastrophic degradation with an extreme wear rate of 1.61 mg/km – 20 times higher than that of electroplated chromium and 9.5 times higher than that of vacuum-arc hard chromium.

Increasing the contact pressure to 9MPa resulted in a proportional rise in the wear rate across all friction pairs while preserving the established tribological hierarchy. Electroplated chromium maintained the highest stability, yielding a wear rate of 0.12 mg/km on both substrates. The wear rate of vacuum-arc hard chromium increased to 0.20 mg/km on VKS-170 steel and 0.24 mg/km on VT-22 alloy. For the molybdenum coating at 9 MPa, the wear rate was 0.26 mg/km on steel and 0.35 mg/km on titanium (fig. 2). The soft chromium coating degraded substantially to 0.34 mg/km on steel and 0.82 mg/km on titanium. Uncoated VKS-170 steel exhibited a wear rate of 0.36 mg/km under 9 MPa. Uncoated VT-22 alloy could not be tested at 9 MPa because spontaneous thermofrictional scuffing and seizure occurred almost instantaneously under these forced contact conditions.

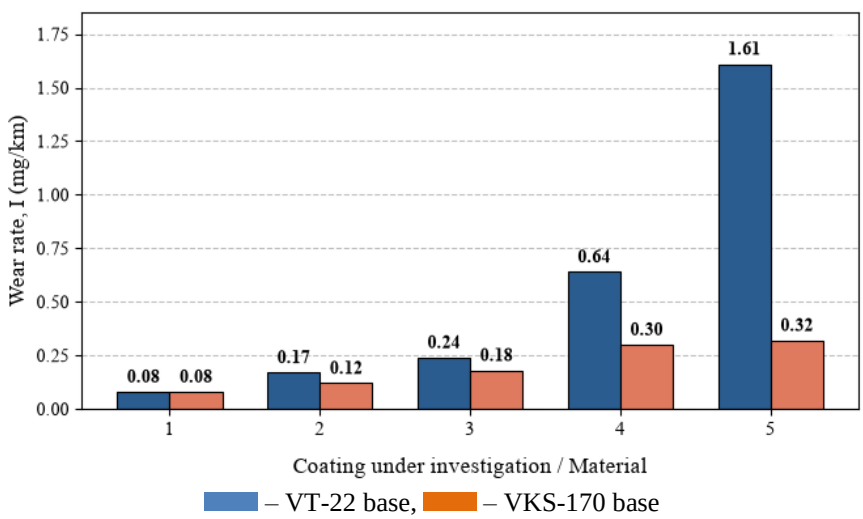


Figure 1. Wear rate bar chart of the friction pairs under a contact pressure of p = 6 MPa: 1 – electrolytic chromium, 2 – vacuum-arc hard chrome, 3 – vacuum-arc molybdenum, 4 – vacuum-arc soft chrome, 5 – without coating (raw material)

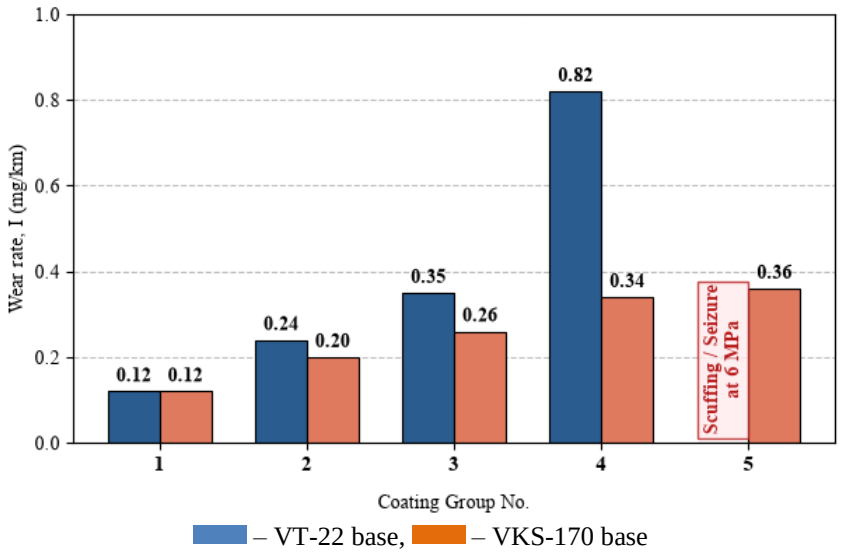


Figure 2. Wear rate bar chart of the friction pairs under a contact pressure of p = 6 MPa: 1 – electrolytic chromium, 2 – vacuum-arc hard chrome, 3 – vacuum-arc molybdenum, 4 – vacuum-arc soft chrome, 5 – without coating (raw material)

The tribological performance of the investigated coatings in AMG-10 fluid is governed by their crystalline architecture and surface adaptation. The durability of electroplated hard chromium stems from fabrication microcracks acting as capillary reservoirs, which entrap lubricant to generate hydrostatic backpressure and sustain boundary lubrication. However, at peak contact pressures (30 MPa), localized breakthrough risks deep subsurface metallic tearing (up to 20 μm), presenting a severe hazard of abrupt failure.

In contrast, dense cathodic vacuum-arc hard chromium exhibits stable oxidative-fatigue wear without spallation, enabled by in situ passivating Cr_2O_3 tribofilms with low shear strength that shield juvenile metallic surfaces from adhesive microwelding.

Vacuum-arc molybdenum provides exceptional tribotechnical stability due to high cohesive binding energy and its elevated melting point. By interacting with residual chamber gases and fluid-borne oxygen, it develops a hard skeleton of dispersed nitrido-oxides (up to 12 GPa) within a compliant matrix. Concurrently, shear-labile Magnéli phase oxides (MoO_3, Mo_nO_{3n-1}) synthesize on real contact asperities as solid self-lubricating barriers, reducing localized shear stresses and ensuring high wear resistance on titanium [16].

Conversely, cathodic vacuum-arc soft chromium degrades rapidly owing to its defective, porous columnar microstructure. Under contact pressures of 6 and 9 MPa, shear stresses induce fatigue cleavage of crystallite tips, releasing hard debris into the friction gap that accelerates abrasive micro-cutting and catastrophic volume loss.

The catastrophic wear of uncoated VT-22 alloy under a contact pressure of 6 MPa and the rapid seizure of the pair at 9 MPa are governed by the low thermal conductivity of titanium ($\lambda \approx 7 – 8$ W/(m·K)). At a sliding velocity of 1.0 m/s, frictional flash temperatures exceeding 800 – 1000 ºC trigger instantaneous thermolysis of the AMG-10 fluid, denuding juvenile metallic contact areas.

The high chemical affinity of heated titanium promotes mutual diffusion with the AISI 1045 steel counterbody, forming brittle intermetallics (TiFe, $TiFe_2$) and initiating adhesive microwelding. Because the thermally softened titanium subsurface yields

under lower shear stresses than the microwelded junctions, rupture occurs cohesively deep within the substrate bulk, transferring material onto the steel counterface. The contact rapidly transitions into a self-mated "titanium-on-titanium" sliding regime accompanied by a surge in the friction coefficient (f > 0.8 –1.0), avalanche thermal escalation, and destructive galling, rendering unmodified titanium entirely unsuitable for sliding pairs against steel.

The 30 – 50% increase in wear rate observed for identical PVD coatings on VT-22 titanium alloy compared to VKS-170 steel is governed by the pronounced disparity in their Young's moduli ($E_{\text{VKS-170}} \approx$ 200 – 210 GPa versus $E_{\text{VT-22}} \approx$ 110 GPa). Under localized contact loading from counterface asperities, the compliant titanium matrix undergoes substantial elastic deflection. Consequently, thin, high-modulus protective films suffer from the "eggshell effect": deprived of rigid mechanical support, they experience cyclic bending that induces high alternating tensile stresses, initiating fatigue microcracking and localized delamination.

In contrast, the stiff VKS-170 steel substrate confines elastic strains strictly to the near-surface frictional shear zone, preventing cyclic flexure of the coating. Electroplated hard chromium serves as the sole exception, yielding identical wear rates on both substrates (0.08 mg/km at 6 MPa and 0.12 mg/km at 9 MPa. Its substantially greater layer thickness entirely absorbs the contact stress field, effectively decoupling coating durability from substrate elastic compliance.

Conclusions.

Sliding friction investigations in an AMG-10 medium confirmed the highest wear resistance for electroplated chromium (0.08 mg/km at 6 MPa and 0.12 mg/km at 9 MPa); however, the ecological toxicity of Cr^{6+} compounds, hydrogen embrittlement, and the risk of particle pull-out restrict its use. Cathodic vacuum-arc hard chromium and molybdenum coatings provide an effective, safe alternative: owing to high adhesion (up to 25 – 35 kgf/mm^2) and protective secondary oxides, they ensure high wear resistance on VT-22 alloy (0.17 – 0.24 mg/km at 6 MPa and 0.24 – 0.35 mg/km at 9 MPa), whereas porous soft chromium degrades rapidly.

The inadmissibility of using uncoated VT-22 alloy in contact with steels was proven due to lubricant pyrolysis, thermofrictional seizure, wear of 1.61 mg/km at 6 MPa, and emergency galling at 9 MPa. The lower elastic modulus of VT-22 titanium alloy compared to VKS-170 steel causes a flexural "substrate effect" and a 30 – 50 % increase in the wear rate of thin PVD layers.

For aerospace hinges and sliding bearings, surface modification of VT-22 alloy with a cathodic vacuum-arc molybdenum or hard chromium coating with a thickness of 50 – 70 μm is substantiated, alongside mandatory scheduled non-destructive testing of the residual layer thickness to prevent abrupt seizure.

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ТЕРТЯ ТА ЗНОШУВАННЯ PVD ТА ГАЛЬВАНІЧНИХ ПОКРИТТІВ ДЕТАЛЕЙ ЛІТАКІВ

Досліджено триботехнічні властивості та зносостійкість вакуумно-дугових (твердий і м'який хром, молібден) та гальванічного покриттів на високоміцному титановому сплаві ВТ-22 і конструкційній сталі ВКС-170 за торцевого тертя ковзання в середовищі робочої гідравлічної рідини АМГ-10 у парі зі сталевим контртілом 45 . Найвищу зносостійкість продемонстрував гальванічний хром , проте екологічні та експлуатаційні обмеження вимагають впровадження чистих технологій. Серед вакуумно-дугових конденсатів шари твердого хрому та молібдену забезпечують стабільно високу трибостійкість на сплаві ВТ-22 за адгезійної міцності до 25 кгс/мм^2 завдяки формуванню вторинних захисних оксидних структур, тоді як м'який PVD-хром швидко руйнується через дефектну стовпчасту будову. Немодифікований титан ВТ-22 зазнає катастрофічного адгезійного задирання внаслідок піролізу мастила та фрикційного мікрозварювання з переходом до заклинювання вузла за 9 МПа. Виявлено контактний «ефект підкладки»: нижчий модуль Юнга титану зумовлює знакозмінний прогин тонких шарів, через що знос PVD-покриттів на сплаві ВТ-22 на 30–50 % вищий, ніж на жорсткій сталі ВКС-170. Обґрунтовано рекомендації щодо осадження товстих PVD-шарів (50 – 70 мкм) для авіаційних шарнірів і підшипників ковзання з обов'язковим регламентним контролем їхньої залишкової товщини.

Ключові слова: титановий сплав ВТ-22, сталь ВКС-170, вакуумно-дугові PVD-покриття, гальванічний хром, молібден, тертя ковзання, рідина АМГ-10, ефект підкладки, адгезійне схоплювання.

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