Tribological and surface morphological characteristics of titanium alloys: a review (postprint)

Authors: Munish Kumar Gupta, Hamza El Etri, Mehmet Erdi Korkmaz, Nimel Sworna Ross, Grzegorz M. Krolczyk, Józef Gawlik, Nafiz Yaşar, Danil Yu Pimenov, Munish Kumar Gupta

Date: 2024-05-12T15:52:00+00:00

Abstract

The ease of fabrication and welding, biocompatibility, high strength-to-weight ratio, capability to withstand temperatures up to 800 °C, and low modulus of elasticity make titanium and its alloys a critical material choice for automotive, biomedical, and aerospace industries. Despite its many advantageous properties, the application of Ti-6Al-4V alloy is limited, particularly regarding its tribological and surface morphological characteristics. Enhancing these properties is crucial, and numerous attempts and studies have been conducted for this purpose. This paper presents a review of the morphological and tribological behaviors of titanium alloys, including Ti-6Al-4V, against different materials such as carbide tools and other material types under dry and lubricated sliding conditions. Surface morphological characteristics, wear behavior, and other relevant properties are discussed in this review article.

Full Text

Preamble

Archives of Civil and Mechanical Engineering (2022) 22:72
https://doi.org/10.1007/s43452-022-00392-x

REVIEW ARTICLE

Tribological and Surface Morphological Characteristics of Titanium Alloys: A Review

Munish Kumar Gupta[1], **Hamza El Etri**[2], **Mehmet Erdi Korkmaz**[2], **Nimel Sworna Ross**[3], **Józef Gawlik**[4], **Nafiz Yaşar**[5], **Danil Yu Pimenov**[6],

Grzegorz M. Krolczyk[1]

Received: 21 December 2021 / Revised: 21 January 2022 / Accepted: 29 January 2022

Abstract

Titanium and its alloys represent a critical material choice for automotive, biomedical, and aerospace industries due to their excellent fabricability, weldability, biocompatibility, high strength-to-weight ratio, ability to withstand temperatures up to 800 °C, and low modulus of elasticity. Despite these favorable attributes, the application of Ti-6Al-4V alloy is limited by its tribological and surface morphological characteristics. Enhancing these properties is essential, and numerous attempts have been made to address this challenge. This paper presents a comprehensive review of the morphological and tribological behaviors of titanium alloys, including Ti-6Al-4V, against various counterface materials such as carbide tools and other material types under both dry and lubricated sliding conditions. The review discusses surface morphological features, wear mechanisms, and other relevant properties.

Keywords: Titanium · Tribological behavior · Surface morphology · Dry sliding · Lubricated sliding

1 Introduction

Following the recognition of titanium alloys' importance for spacecraft, aircraft, missiles, medical devices, automotive components, and other applications [1], the US government began funding titanium research initiatives. At that time, titanium was considered the first structural material to receive such significant scientific, financial, and political attention. A major milestone occurred in 1965 when Per-Ingvar Branemark utilized titanium in the first dental implant [2]. As noted above, titanium alloys possess numerous beneficial characteristics; they are employed in heat exchangers due to their high-temperature resistance and in aircraft engines because of their lightweight nature. Titanium is 45% lighter than steel yet offers comparable strength [3]. Additionally, titanium alloys are used in tools and jigs for molten metal processing due to their low thermal conductivity [4]. Their strength-to-weight ratio makes them suitable for biomedical and various other applications [5]. Ti alloys have long been considered among the most desirable materials in aerospace and automotive industries because of their tremendous weight savings and specific strength advantages over Ni-base superalloys. The ductility of Ti alloys can be improved by incorporating Nb and Cr elements, while their strength and creep resistance at temperatures exceeding 800 °C can also be enhanced [6, 7].

Titanium alloys exhibit tensile strengths ranging from 20,000 to over 200,000 psi, with high-cycle fatigue capability and a melting point of 1668 °C [8]. There are four categories of titanium alloys: alpha, beta, alpha–beta, and pure grades [9], each offering specific properties for different applications. Pure titanium contains no alloying elements, making it very ductile but relatively low in strength [10]. Alpha alloys provide reliable strength at high temperatures and are readily weldable, typically containing aluminum [11]. Beta alloys are primarily used for applications requiring high tensile strength and are heat-treatable unlike alpha alloys [12], utilizing stabilizers such as silicon or molybdenum. Alpha-beta alloys are the most commonly used titanium alloys because they combine the best qualities of both types, offering a balance between corrosion resistance, weight, and average strength [13]. These alloys are heat-treatable and incorporate both beta and alpha stabilizers [14]. Ti–6Al–4V (Ti64), also known as grade 5 titanium alloy [15], is used worldwide for high-temperature applications up to approximately 315.55 °C. In addition to its good ductility, its strength can be increased through heat treatment [16]. This grade contains 4% vanadium and 6% aluminum [17] and is widely used in automobiles, reaction equipment, aircraft, biomedical applications [18], and other industries [19].

Titanium and its alloys exhibit poor wear resistance, tribological properties, and fretting behavior when sliding against even softer materials [20]. Low thermal conductivity is one of the primary causes behind the weak tribological characteristics of titanium, mainly resulting from low shear strength and dislocation of the thin titanium dioxide film, leading to accelerated wear on the alloy’ s surface [21]. Other disadvantages include unstable and high coefficient of friction (COF), limited load-bearing capacity, low adhesive and abrasive wear resistance, and low hardness [22]. These limitations have motivated tribologists to improve the surface morphological and tribological properties through various approaches, including chemical treatment, thermal oxidation, tribo-film generation, surface hardening, chemo-thermal treatment, surface texturing, coatings, and counter-body selection [23].

The tribological behavior of titanium alloys can be determined using several established methods; however, appropriate procedures should be selected based on the specific application to enhance their tribological performance [24]. Comprehensive research on the tribological properties of Ti–6Al–4V against various counter bodies under different environmental and operating conditions is therefore crucial [25]. The primary tribological parameters to investigate are friction and wear [26]. Common experimental methods for determining wear characteristics include abrasive wear tests, sliding wear tests, and slurry corrosion tests. Tribometers can conduct sliding wear tests at elevated temperatures using disc-on-disc, ring-on-disc, pin-on-disc configurations, etc. [27]. Cutting tools made from diverse materials such as CBN, ceramics, carbides, and PCD are subject to wear mechanisms including diffusion, chemical dissolution, and adhesion [28]. Tool wear represents the most significant tribological issue when machining titanium alloys, with the most common wear observed on the flank and rake faces of cutting tools [29, 30]. This wear substantially affects machining performance in terms of power consumption [31], cutting temperature [32], surface finish, etc. [33]. PVD-TiAlN-coated cutters are used for machining titanium alloys to enhance tribological properties due to their excellent wear resistance, good chemical stability, and high hot hardness [34]. Cutting tool grade and material selection are critical when working with titanium alloys. Basic knowledge of cutting tool performance is essential for proper material selection, considering component shape and type, required surface quality, and machining conditions [35]. Various tool grades with distinct properties are used to achieve different combinations of tensile strength, wear resistance, and hardness. Generally, a successful cutting tool should be tough (resistant to bulk breakage), hard (resistant to deformation and flank wear), chemically stable (resistant to diffusion and oxidation), and thermally stable [36, 37]. Carbide inserts are the most widely used tools in the machining industry [38–40]. Carbide is a chemical compound of carbon with an electronegative element, classified into metal carbides (tungsten, tantalum, vanadium, titanium) [41] and non-metal types (boron, silicon, calcium). Metal carbides are primarily used as cutting tools due to their high-temperature resistance and extreme hardness, making them suitable for cutting, drilling, polishing, and grinding [42, 43].

2 Features and Applications of Titanium Alloys for the Aerospace Industry

Titanium has been utilized in the aerospace industry for many years because of its lightweight, exceptional corrosion resistance, and good strength. The demand for titanium alloys is increasing due to their compatibility with CFRP (Carbon Fiber Reinforced Polymer) regarding coefficient of thermal expansion [44]. The International Titanium Association (ITA) reported in 2012 that titanium demand would continue to grow. In 1985, Sumitomo Metal and Nippon Steel began commercial production of titanium alloys after obtaining qualifications from Rolls-Royce and other major domestic manufacturers, using these alloys for aircraft engines. The company also began supplying pure titanium to Airbus for airframe applications in 2002 [44]. The microstructure of the commonly used Ti6Al4V alloy is shown in Fig. 1 [Figure 1: see original paper].

Titanium can be machined economically depending on the material’ s physical parameters [46]. Since various titanium alloy grades exhibit different machining characteristics, appropriate tooling and conditions must be selected. Better machinability and tool life can be ensured by following these recommendations [47]: - Using a rigid setup between workpiece and tool - Maintaining sharp tools to reduce galling and heat buildup - Applying ample cutting fluid for maximum heat removal - Regularly removing chips from the machine

Different titanium alloy grades, their chemical compositions, and properties are listed in Table 1 [48]. Titanium alloys are employed in numerous aircraft applications including airframes (for weight reduction), engines (fans and compressors), and other components as shown in Table 1 [44]. During flight, external temperatures can reach -60 °C or lower; fortunately, titanium exhibits good resistance to such low temperatures. Moreover, due to their high strength, titanium alloys are used to manufacture many critical aircraft engine and structural components [49]. These alloys also demonstrate high corrosion resistance, fatigue resistance, and wear resistance.

Experimental and theoretical studies on titanium alloy wear behavior continue because aircraft engine and structural components, as well as aerospace and military parts, are typically produced through casting or machining. The rationale for using titanium alloys in aircraft applications is summarized in Table 1 [44]. Titanium is also deployed in scaffolds and biomedical implants as shown in Fig. 2 [Figure 2: see original paper].

---

3 Wear Behavior of Titanium and Its Alloys

Wear behavior describes the surface interaction that leads to material removal and deformation during sliding [60]. This parameter is also defined as dimensional loss due to plastic deformation. Wear can result from erosion, corrosion, chemical processes, or combinations thereof [61]. Various wear types include: abrasive wear (material loss from hard surface sliding causing scratches or corrugations), adhesive wear (debris welded to the material surface), surface fatigue (surface weakening from cyclic loading), erosive wear (caused by sharp particle interaction), and fretting wear (small surface shifts under load) [20]. Standard experimental methods are approved for evaluating wear behavior of different metals, with examinations performed at specific intervals and defined conditions. The wear coefficient correlates and measures material wear [21]. Testing can be conducted using disc-on-disc, ball-on-disc, ring-on-disc, and pin-on-disc devices. The pin-on-disc apparatus, where a pin contacts a rotating disc (Fig. 3 [Figure 3: see original paper]), applies force to the pin while measuring friction via strain-gauge sensors. The wear coefficient for both pin and disc is calculated based on material loss during testing. Pin-on-disc tests are important for estimating surface COF, wear resistance, adhesion, and lubricity parameters [22].

Ti and its alloys are known for poor wear properties. Ti surfaces easily gall when in contact with other metals under sliding, fretting, or contact conditions [62].

3.1 Wear of Titanium and Its Alloys Versus Metallic Counter Bodies

3.1.1 Dry Sliding Conditions This section focuses on the wear behavior of Ti–6Al–4V alloy against different metallic counterfaces at ambient temperature under dry sliding conditions. To understand tribological parameters, Molinari et al. [64] performed dry sliding wear tests on Ti–6Al–4V using the disc-on-disc method at constant humidity and ambient temperature. Specimens measured 40 mm in diameter and 10 mm thickness. Tests were conducted at sliding velocities of 0.3-0.8 m/s for a sliding distance of 1770 m, with both specimens made of Ti-6Al-4V alloy. They observed that increasing applied load led to higher wear volume as shown in Fig. 4 [Figure 4: see original paper]. Wear volume variation showed no significant changes with different sliding speeds, though a minimum wear rate occurred at intermediate sliding speeds. The findings indicated limited plastic deformation even at low loads and poor surface oxide protection. The authors emphasized that improving surface mechanical properties is important to prevent plastic deformation and delay thermal softening, as these parameters cause mechanical instability and promote delamination. The overall research focus was understanding the wear transition from delamination to oxidative wear [64].

Hager et al. [65] examined Ti-6Al-4V disc against a Ti-6Al-4V pin counter body to study fretting wear behavior at ambient temperature and 450 °C. At 30 Hz oscillation frequency, four tests were performed with stroke lengths of 45-230 m. A 200 N normal load was applied, decreasing by 10 N every 3 minutes until reaching zero. Frictional hysteresis was measured using a piezoelectric transducer and laser technique. Ambient temperature fretting tests revealed slip fretting at higher loads [65].

Titanium-steel pairs are commonly used in tribological applications, with numerous studies examining this relationship. Straffelini et al. [66] investigated the tribological interaction between Ti-6Al-4V and AISI M2 steel. Wear test discs were 40 mm thick with 0.3 µm surface roughness. Sliding experiments used a disc-on-disc configuration under loads of 50, 100, and 200 N at sliding speeds of 0.3-0.8 m/s. Steady-state conditions were achieved at 1770 m sliding distance with the counter disc fixed. Counterface discs were either Ti-6Al-4V alloy or quenched and tempered AISI M2 tool steel. Results showed minimum wear rate at 0.6 m/s with Ti-6Al-4V counter disc, while wear rate decreased with increasing speed for steel counter discs. Wear rates increased significantly with applied load, though the increase was modest. Friction coefficients ranged from 0.3 to 0.4, with peak values (0.35-0.4) at minimum sliding speed. SEM images of debris formation are presented in Fig. 5 [Figure 5: see original paper] [66].

Alam and Haseeb [67] studied tribological characteristics of Ti-24Al-11Nb and Ti-6Al-4V against hardened steel under dry sliding conditions. Wear tests were performed using a pin-on-disc apparatus at room temperature with loads of 15-45 N. Specimens were cleaned with acetone and dried before each test. The wear rate of Ti-6Al-4V increased rapidly before reaching steady state, with higher loads causing increased wear rates. Ti-24Al-11Nb showed significantly lower wear rate—approximately 48 times lower than Ti-6Al-4V. The wear scar on Ti-24Al-11Nb is shown in Fig. 6a [Figure 6: see original paper], with wear debris for both alloys presented in Figs. 6b and 6c [67].

Wear behavior is influenced by operating parameters including sliding distance, velocity, and normal stress. Qiu et al. [68] investigated wear characteristics of Ti-6Al-4V alloy under dry sliding at high speeds of 30-70 m/s. Pin-on-disc tribometer tests used Ti-6Al-4V pins against GCr15 steel discs at contact pressures of 0.33, 0.67, 1, and 1.33 MPa for 100 s duration. COF was recorded throughout testing, and friction-induced thermal effects were studied using thermocouples positioned 3, 6, and 9 mm from the pin center. The authors noted that COF decreased with increasing sliding speed at 1 and 1.33 MPa contact pressure. With temperature increase, Ti-6Al-4V COF initially rose then dropped rapidly, while wear rate slowly increased to a constant value before rising sharply. Tribological properties were affected by mechanical-thermal parameters: as sliding speed increased, the metallic Ti fraction decreased while oxide proportion increased on damaged surfaces [68].

Cui et al. [69] studied wear properties of Ti-6Al-4V at temperatures from 20 to 400 °C under dry sliding using a pin-on-disc tester with GCr15 steel counter body. Tests were performed in ambient air at loads of 50, 100, 150, 200, and 250 N, sliding distance of 1.2×10^3 m, and sliding speed of 1 m/s. At 20 °C, wear loss increased linearly with load. At 200 °C, wear loss increased linearly across 50-150 N load range. At 400 °C with 50-100 N load, wear loss decreased abruptly, marginally increased from 100-200 N, then rose rapidly above 200 N [69].

Fellah et al. [70] investigated tribological properties of Ti-6Al-4V against 100Cr6 steel balls for hip prosthesis applications using ball-on-disc and pin-on-disc tests. Rotational speed and applied load were varied in ambient air conditions. The authors found that periodic formation and fracture of transfer layers caused large friction fluctuations, with higher COF at elevated sliding velocities.

Jayachandran et al. [71] studied dry sliding wear performance of Ti-6Al-4V pins against SS316L stainless steel discs at constant contact pressure. High-temperature sliding tests were conducted at speeds of 0.01-1.5 m/s. Wear rates decreased marginally with sliding velocity up to 0.5 m/s, after which beneficial effects diminished.

Liu et al. [72] performed wear tests using a pin-on-disc apparatus with Ti-6Al-4V pins and GCr15 steel discs. Ti-6Al-4V specimens were heated to 760 °C for 60 minutes then cooled to 35 HRC hardness, while steel specimens were water-quenched at 840 °C and tempered at 150 °C to 62 HRC. The 9 mm diameter, 20 mm long pin slid against a 70 mm diameter, 10 mm thick disc. Both surfaces were ground to roughness values of 0.42 μm (pin) and 3.20 μm (disc). Tests were conducted at 30 N normal load, 0.2-1.2 m/s sliding speed, and 1000 m sliding distance. COF ranged from 0.33-0.56 at low temperature and 0.68-0.84 at ambient temperature. Ti-6Al-4V wear rate increased with sliding speed at both temperatures, showing approximately linear variation at ambient temperature. Surface morphology parameters were affected, with damage observed on surfaces at low temperature.

Conradi et al. [73] explored the tribological response of laser-textured Ti-6Al-4V under dry and lubricated conditions using Hank's solution. Titanium alloy grade

5 in aged-and-solution condition was used. Alloy sheets (1.55 mm thick) were cut into 25 mm diameter discs, hand-ground with 600-grit paper to 0.185 µm surface roughness. Laser texturing was performed using an LPKF nanosecond laser at 100 mm/s for dimples and 300 mm/s for lines. Ball-on-flat tribological tests were conducted under reciprocating sliding at 5 N load, 1 GPa contact pressure, 5 mm/s sliding velocity, and 1000 m sliding distance in both dry and fully flooded lubricated conditions. Surface morphological behavior of Ti grade 5 improved, with dimples showing lowest COF under dry conditions, while wear resistance showed promising results for both conditions.

Mao et al. [74] conducted dry sliding wear experiments on Ti-6Al-4V using a pin-on-disc method at 50-250 N normal load and temperatures of 25-500 °C. The authors investigated worn surface and subsurface composition and morphology of tribo-layers. Ti grade 5 alloy pins (Fig. 7 [Figure 7: see original paper]) slid against GCr15 steel discs. Wear rate increased linearly with load at 25-200 °C. At 400-500 °C with 50-100 N load, wear rate reached minimum values, marginally increased at 100-200 N, then rose rapidly above 200 N. Delamination, adhesion, and abrasive wear occurred at 25-200 °C, while oxidative wear dominated at 400-500 °C.

Jozwik [75] investigated tribological performance of Ti grade 5 alloy at room and elevated temperatures (150 °C) using a ball-on-disc tribometer with Ti-6Al-4V discs and aluminum oxide (Al_2O_3) balls. At 5 N normal load, 0.3 m/s speed, and 400 m sliding distance, volumetric wear was average at room temperature but increased at elevated temperature. The wear rate was 0.52 at room temperature, decreasing to 0.49 at elevated temperature.

Wang et al. [76] examined wear behavior of two Ti alloys (Ti-6Al-4V, TC11) against AISI 52100 steel at 25-600 °C. Tests were performed at 50-250 N normal load using a pin-on-disc apparatus at 1 m/s sliding speed and 1.2×10^3 m sliding distance under dry sliding. Both alloys exhibited severe-to-mild wear transition at critical temperatures of 400 °C (TC4) and 300 °C (TC11), showing better wear performance above these temperatures.

Feng et al. [77] investigated quenching effects on Ti-6Al-4V wear properties using water, oil, or liquid nitrogen quenching media. Pin-on-plate wear tests were conducted with a diamond tip at 5 N normal load and 50 rev/min sliding speed under dry conditions. Surface hardness increased from 400 to 800 VHN with quenching, though this did not improve wear resistance.

Other studies examined lubricated conditions against various materials. Yang et al. [78] studied tribological performance of titanium alloys against tungsten carbide under oil and aqueous lubrication using a ball-on-disc apparatus with tungsten carbide balls and TC4 titanium alloy discs. Oil lubrication reduced friction, while SEE aqueous lubrication showed good anti-wear behavior by significantly decreasing abrasive and adhesive wear.

Luo et al. [79] investigated bio-lubricant effects on Ti-6Al-4V tribological performance. Grade 5 Ti alloy squares (5 mm thick) were tested against 4 mm silicon nitride (Si_3N_4) balls using a ball-on-flat apparatus under dry and three lubricant conditions at 9.8 N load, 4 mm/s sliding velocity, and 6 mm sliding length. COF fluctuated heavily and wear rate was high under dry conditions. Lubrication with physiological saline, bovine serum, and deionized water reduced both wear rate and COF, with bovine serum providing the best results.

Alagic et al. [80] compared tribological performance of orthopedic implant materials Ti-13Nb-13Zr and Ti-6Al-4V grade 5 alloy using a block-on-disc apparatus at 20-60 N load and 0.26-1 m/s sliding velocity. Ti-6Al-4V showed better wear resistance compared to Ti-13Nb-13Zr.

3.2 Wear of Titanium and Its Alloys Against Carbide

Carbide tools are used for material removal during machining, with coatings improving physical properties. Worn carbide tool examples are shown in Fig. 8 [Figure 8: see original paper]. Dry machining produces parallel abrasion lines along cutting insert noses due to lack of lubrication. Under MQL conditions at specific cutting speeds, tool wear is less severe with no built-up edge or tool fracture, as a lubricating layer forms between insert and workpiece [81].

Liang et al. [82] conducted physicochemical analysis of WC-6Co cemented carbide against Ti-6Al-4V using pin-on-disc at high temperature. Uncoated carbide pins slid against Ti-6Al-4V discs (43 mm diameter) at 4 mm pin diameter. Temperature was controlled at 20, 320, 620, and 920 °C with 100 N hydraulic load. Lower COF and more stable behavior occurred at high temperature (920 °C), with COF decreasing from 0.56 at 20 °C to 0.36 at 920 °C (Fig. 9 [Figure 9: see original paper]). Tribological track depth increased eightfold from 27 µm at 20 °C to 253 µm at 920 °C, softening the Ti-6Al-4V alloy and significantly reducing wear resistance.

Yang et al. [83] examined wear and friction performance of Ti alloy against tungsten carbide lubricated with phosphate ester. Ti-6Al-4V and WC-Co materials were tested using a ball-on-disc apparatus under various lubricating environments. The disc was hardened Ti-6Al-4V (35 HRC) and the ball was 10 mm tungsten carbide. Specimens were cleaned with ethanol and acetone before testing. The 100 N applied load produced COF results dependent on lubricant type. With deionized water, COF increased from 0.3 to 0.45 with sliding time, failing to effectively lubricate the tungsten carbide/Ti-6Al-4V pair. Triethanolamine borate, considered a good lubricant and anti-wear additive, produced high COF (~0.4) similar to water. Emulsion provided better lubrication, maintaining stable COF of 0.18. Adding 1 wt% phosphate ester (PPE) lubricant was optimal—COF initially unstable but rapidly decreasing to 0.14 and remaining stable (Fig. 10 [Figure 10: see original paper]). The authors concluded PPE provides effective lubrication for Ti-6Al-4V/tungsten carbide tribo-pairs. Figure 11 [Figure 11: see original paper] shows 3D wear track images with various lubricants.

Egana et al. [84] studied heat partition and friction coefficients during machining of Ti-6Al-4V against cemented carbide. Cylindrical Ti-6Al-4V bars were tested against polished cemented carbide pins. Each friction test lasted 10 s at sliding velocities of 10-100 m/min and contact pressures of 750, 1300, and 1500 MPa under 100, 600, and 1000 N loads, mostly in dry conditions with some emulsion-lubricated tests. COF decreased with increasing sliding speed. Ti adhesion on carbide pins became denser at higher contact pressure or sliding speed (>0.75 GPa or 60 m/min), with shearing occurring between bulk material and adhesive layer. This effective adhesion is the primary cause of rapid tool wear beyond 60 m/min sliding speed. The heat partition coefficient decreased from 50% to 30% as sliding speed increased from 10 to 100 m/min.

Courbon et al. [85] examined tribological characteristics of Ti-6Al-4V and Inconel 718 against carbide tools under cryogenic and dry machining conditions. Cylindrical bars of Inconel 718 (hot rolled, aged, solution treated) and Ti-6Al-4V (annealed, quenched) were tested against spherical cemented carbide pins (10% Co, 90% WC). TiN-coated pins (4 μm) were used for Inconel 718 tests, while uncoated pins were used for Ti-6Al-4V. Each 10 s friction test used 1000 N normal load at 10-100 m/min cutting speeds under dry, cryo gas, and cryo liquid conditions. Ti-6Al-4V COF slightly decreased with sliding speed, while cryogenic fluid addition (gas or liquid nitrogen) had minimal effect (COF remained 0.2-0.3). Liquid nitrogen' s high cooling potential reduced heat transmission.

Patil [87] investigated tribological performance of solid WC-Co carbide under dry sliding using cemented carbide pins, Ti-6Al-4V discs, and molybdenum disulfide powder or SAE-40 oil lubricants. Molybdenum disulfide was used for damage protection and friction/wear reduction. Pin-on-disc tests were conducted under three conditions: dry, solid lubricant, and oil lubricant (Table 2). The author examined COF, wear behavior, and maximum temperature versus sliding velocity. Solid lubrication produced better COF and tool wear results compared to other environments, with both disc (Ti-6Al-4V) and pin (WC-Co) performing optimally. Temperature remained nearly linear and stable with solid lubricant, increased slightly with oil lubricant, and rose rapidly under dry sliding.

Jadhav et al. [88] studied wear performance of coated carbide tools using electrostatic spray coating (ESC) of YSZ nanoparticles on tungsten carbide substrates. The coating served as thermal partition for high-temperature applications. Ti-6Al-4V alloy was tested in two configurations: (1) Ti-6Al-4V disc against uncoated tungsten carbide pin, and (2) Ti-6Al-4V disc against YSZ-coated tungsten carbide pin. Dry sliding pin-on-disc tests were conducted at 500 rpm with 20 N fixed load and sliding speeds of 0.75, 1.25, 1.75, 2.25, and 2.75 m/s for 30 minutes. Coated pins showed better performance parameters, while uncoated pins exhibited worn surfaces with degradation, deep grooves, and wear debris in the sliding direction. YSZ coating provided tungsten carbide with good thermal shock durability.

Niu et al. [89] examined wear and friction characteristics of TC4, TC18, and TA19 titanium alloys against tungsten carbide under water lubrication and dry sliding. Reciprocating sliding tests were performed at 112 m/s sliding velocity, 3 N load, and 20 minute duration with water lubrication (26 °C, 30% humidity) and dry conditions. Under dry sliding, COF increased from 0.24 to 0.32 for TC4, 0.28 to 0.40 for TC18, and reached 0.34 for TA19 within 2 minutes. Water lubrication reduced COF and wear size for TC4 and TA19 but did not affect TC18 COF.

Qu et al. [90] explored sliding wear and friction of Ti alloys against polymer, ceramic, and metal counterfaces. Ti-6Al-4V and Ti-6Al-2Sn-4Zr-2Mo (Ti6242) alloys (Fig. 12 [Figure 12: see original paper]) were tested via pin-on-disc against stainless steel (metal), silicon nitride and alumina (ceramics), and PTFE (polymer). Ti discs were 63.5 mm diameter and 12.7 mm thick. Tests were performed at 10 N normal load and 500 m sliding distance in ambient air (52-62% humidity, 18-22 °C). Both Ti alloys showed similar wear and friction performance regardless of composition. Friction fluctuations were large for ceramic and metal balls sliding on titanium discs, with higher COF and considerable fluctuation at lower sliding velocities.

Xuedong et al. [91] investigated tribo-chemical behavior of titanium/tungsten carbide pairs under aqueous lubrication. High-speed block-ring tests were conducted at 100 N normal load, 1.28 m/s rotational velocity, and 300 s duration. Boron-containing additives showed the best anti-wear behavior.

Çalışkan and Küçükköse investigated aCN/TiAlN coating effects on chip morphology, surface finish, and tool wear in face milling of Ti grade 5 alloy. AISI D2 steel discs (3 mm thick, 25 mm diameter) and carbide milling specimens were used. aCN/TiAlN coating was applied via magnetron sputtering. Pin-on-disc wear tests were performed at 10 cm/s sliding velocity and 5 N load at 25 °C. The aCN/TiAlN coating showed 19% higher adhesion than AISI D2 steel in scratch tests, with aCN coating exhibiting 95% lower wear rate and 76% lower COF against alumina balls. The aCN/TiAlN coating also produced higher resultant cutting forces than commercial tools.

Cadena et al. [92] examined PVD (AlCrN) coating effects on tool deterioration when machining Ti alloys. Pin-on-disc tests showed the coating exhibited low wear rate and COF compared to previous studies [93].

Medina et al. [94] evaluated tribological behavior of grade 5 Ti alloy against various coated CW pins. Ti-6Al-4V alloy sheets were tested against three insert types (H13A, 1105, 4025) coated with (Ti, Al)N_2 and TiN. Pin-on-disc tests were performed under dry and lubricated conditions using molybdenum disulfide solid lubricant and SAE 5W-30 oil at 0.55 m/s sliding velocity and 50 N load. Oil lubrication increased COF but created a protective debris-oil layer. Lower COF values were obtained in dry or solid lubrication conditions.

El-Tayeb et al. [95] examined cryogenic performance effects on Ti alloys. Ti-5Al-4V-0.6Mo-0.4Fe (Ti54) and Ti-6Al-4V specimens (Fig. 13 [Figure 13: see original paper]) were tested as pins against tungsten carbide plates using a pin-on-ring device under dry and cryogenic (liquid nitrogen) conditions at various loads, speeds, and durations. Ti54 COF decreased under all conditions, while Ti-6Al-4V COF increased at high loads and sliding times.

A summary of previous studies is provided in Table 3 .

---

4 Overview on Surface Modifications and Tribological Behavior Improvement Methods for Titanium and Its Alloys

4.1 Different Methods to Improve Surface and Tribological Characteristics

Surface characteristics of materials often require modification for adhesion, biocompatibility, wettability, etc. Various treatment methods have been implemented to improve tribological behavior, surface morphology, and material structure. Revankar et al. proposed ball burnishing to enhance Ti-6Al-4V wear resistance. Ti-6Al-4V bars (12 mm diameter) were processed using an Ace turn-mill CNC Fanuc lathe for burnishing and turning tests under SAE-40 oil lubrication. The ball burnishing approach showed promise as an effective surface treatment, increasing surface microhardness from 340 to 405 HV and reducing surface roughness from 0.45 to 0.12 µm. COF decreased as burnishing force increased.

Quan et al. [101] developed an effective lubricant consisting of polyethylene glycol (PEG) and Zn nanoparticles. Ball-on-disc wear tests were performed at 100 N load for 60 minutes at 25 °C and 20-30% humidity. Ti-6Al-4V discs were polished and abraded for smoother surfaces. Zn nanoparticles in PEG produced low COF, with stable oxide films preventing direct contact between friction pairs and providing better boundary lubrication.

Ion implantation is an economical, viable method for enhancing surface morphological and tribological performance. Carbon or nitrogen ions accelerate and embed into the material surface (not a coating but implantation into the substrate matrix) at depths of 0.1-0.3 µm over 2-10 hours. Allen et al. [102] examined ion-implanted ultra-high molecular polyethylene against grade 5 Ti alloy using pin-on-disc tests at 5 MPa load and 0.25 m/s sliding speed in water-lubricated and dry environments. Ti alloy oxidation improved mechanical properties and surface hardness, while ion implantation provided superior surface performance and wear resistance.

Yilbas et al. [103] inspected mechanical and tribological effects of plasma nitriding on Ti-6Al-4V. Nitrided and untreated Ti specimens were tested using a pin-on-disc apparatus under ET025 oil lubrication at 35 rev/min, 1 N load, and 25-30 mm/s sliding speed with AISI 52100 steel balls. Plasma nitriding improved wear resistance.

Oñate et al. [104] examined ion implantation effects on tribological performance of various alloys including Ti-6Al-4V, finding reduced frictional coefficient. Itoh et al. [105] studied nitrogen ion implantation effects on Ti-6Al-4V tribological features. Disc specimens (3 mm thick) were implanted with nitrogen ions and tested against ASTM 52100 steel balls at 460 N load, 0.04 m/s sliding speed, and 1 hour duration under SAE 7.5W-30 oil lubrication. Nitrogen-implanted Ti-6Al-4V showed lower COF and reduced volumetric wear rate for both steel balls and titanium discs.

Azghandi et al. [106] studied friction stir processing effects on pure Ti alloy surface improvement. Ti grade 2 shoulder tools and tungsten carbide pins were used. Increased friction stir processing reduced wear and debris, decreasing wear rate and transforming wear mechanism from adhesive to abrasive.

Guleryuz et al. [107] evaluated thermal oxidation effects on grade 5 titanium alloy wear performance under dry sliding. Surface hardness increased from 450 to 1300 HV after 60 hours oxidation at 600 °C, significantly improving wear resistance. Wear tracks for untreated and oxidized alloys are shown in Fig. 14 [Figure 14: see original paper].

4.2 Surface Texturing to Improve Surface and Tribological Characteristics

Surface texturing creates micro-structures (e.g., lubricant reservoirs) on material surfaces to enhance tribological and friction behavior while reducing wear. Pratap and Patra [108] found that mechanical surface modification improved Ti-6Al-4V wettability and tribological behavior [109]. Their study used three mechanical micro-tools (micro drill, micro flat end mill, micro ball end mill) to produce micro-dimples. The micromachining process effectively created micro-dimpled surfaces with various end geometries. Ti-6Al-4V wettability improvement resulted from the roughness factor created by surface texture. Micro drill textured surfaces (MDTS) and micro ball-end textured surfaces (MBETS) showed enhanced wettability compared to other surfaces, making them suitable for biomedical implants. MBETS exhibited the lowest COF due to improved wettability, increased surface hardness, and ability to trap wear debris within micro-dimples.

Ghosh et al. [110] found that surface texturing did not provide significant wear resistance under high loads. Kang et al. [111] examined combined surface texturing and nitriding effects on Ti alloy tribological performance. Ti-6Al-4V samples were nitrided at 750-950 °C for 10 hours in a plasma nitriding furnace. Ball-on-disc tests showed improved wear resistance, with wear rate decreasing then increasing with nitriding temperature, reaching minimum at 900 °C. COF increased due to roughness. The combination of surface texturing and nitriding reduced wear rate and COF at high nitriding temperatures.

Singh et al. [112] investigated textured tool wear effects when cutting Ti-6Al-4V under graphene-assisted lubrication. Better wear resistance performance was observed under lubrication as shown in Fig. 15 [Figure 15: see original paper].

4.3 Surface Coatings to Improve Surface and Tribological Characteristics

Various coating procedures improve surface characteristics and reduce wear rates and friction, including plasma nitriding, metal nitriding, sputtering, laser cladding, laser treatments, and laser gas alloying. These techniques enhance both physical and mechanical surface properties, with proper coating selection being critical.

Hsu and Li [113] reported that hydrothermal treatment improved Ti-6Al-4V tribological performance. Ti-6Al-4V surfaces were treated in urea solution with or without subsequent heat treatment. Increasing urea concentration decreased hydrophilicity, increased hardness, and reduced surface roughness. The T0.5 sample showed the lowest contact angle (Fig. 16 [Figure 16: see original paper]), with contact angle increasing with urea solution content.

Datta et al. [114] applied TiN coatings to Ti-6Al-4V using cathodic arc deposition. Coating hardness (33.41 ± 10 GPa) was approximately seven times higher than uncoated Ti-6Al-4V, with wear rate decreasing about fourfold compared to the uncoated alloy.

Danisman et al. [115] examined TiAlN, TiCN, and TiN coating effects on Ti-6Al-4V wear resistance. Tests were performed at various loads and sliding speeds at room temperature under dry sliding. TiCN coating provided the lowest surface roughness, followed by TiN coating, uncoated Ti-6Al-4V, TiAlN, and TiCN. TiN coating provided better wear rate and friction results compared to uncoated and other coated conditions.

Shao et al. [116] evaluated surface coating effects on Ti-6Al-4V wear performance. Alumina-reinforced aluminum was cold-sprayed onto the alloy, then processed with plasma electrolytic oxidation (PEO). The combined PEO and cold-sprayed coating exhibited the finest wear resistance compared to untreated Ti-6Al-4V, demonstrating that this combination is a promising method for improving Ti alloy wear performance.

Roy et al. [117] investigated Hank’ s solution effects on Cr_3C_2-NiCr coated Ti grade 5 alloy wear performance. The coated specimen showed improved wear resistance and hardness compared to the substrate. Surface texturing methods effectively reduced COF for various biomedical implants and applications (Table 4).

---

5 Conclusions

- Titanium offers many desirable characteristics including light weight, high strength, and good corrosion resistance. Titanium alloys provide higher strength than light metal alloys, steels, and nickel alloys based on specific yield strength-to-density ratios.

- This metal is divided into several types and grades with various chemical compositions and mechanical properties. The widespread use of titanium alloys, especially grade 5, in biomedical, automotive, and aerospace applications makes them important materials for lightweight applications, despite machining difficulties.
- Understanding titanium' s tribological behavior and improving wear and friction coefficient performance is essential.
- Titanium alloys exhibit strong adhesion, severe adhesive wear, and high, unstable friction when sliding against most engineering materials due to their crystal and electronic structure, poor lubrication, and low thermal conductivity.
- Besides poor abrasion resistance, titanium alloys have low hardness that cannot be significantly improved by heat treatment. Their high adhesion tendency makes them prone to fretting damage when combined with stainless steels, with fretting wear damage serving as fracture initiation sites.
- This review summarizes various studies on tribological characteristics of titanium alloys, particularly Ti-6Al-4V, under dry and lubricated sliding against different counterface materials in diverse environmental conditions.
- The review covers counter body types, input parameters, tribological performance, test methods, environmental conditions, lubricants, titanium alloy behavior, and surface modification techniques for tribological and morphological improvement.
- Future work should explore different materials and tribological characteristics, including environmentally friendly lubricants and greases to address tribological issues.

Funding

The authors thank the Polish National Agency for Academic Exchange (NAWA) No. PPN/ULM/2020/1/00121 and National Science Centre (NCN) Project No. UMO-2020/37/K/ST8/02795 for financial support. This work was also supported by the National Centre of Science decision No. 2017/25/B/ST8/00962.

Declarations

Conflict of interest: The authors declare no competing interests.

Ethics approval: Authors state that the research was conducted according to ethical standards.

References

1. Krajewska-Śpiewak J, Gawlik J, Piekoszewski W, Stachura K. Identification of residual stresses in a surface layer of Ti6AL4V and inconel 718 after process of peripheral milling. *Tehnički vjesnik*. 2018;25(1):88. https://link.gale.com/apps/doc/A534958063/AONE?u=anon~ec0705f8&sid=googleScholar&xid=13c202
2. Sullivan RM. Implant dentistry and the concept of osseointegration: a historical perspective. *J Calif Dent Assoc*. 2001;29:737–45.
3. Lyasota I, Kozub B, Gawlik J. Identification of the tensile damage of degraded carbon steel and ferritic alloy-steel by acoustic emission with in situ microscopic investigations. *Arch Civ Mech Eng*. 2019;19:274–85. https://doi.org/10.1016/j.acme.2018.11.012.
4. Saleem W, Salah B, Velay X, Ahmad R, Khan R, Pruncu CI. Numerical modeling and analysis of Ti6Al4V alloy chip for biomedical applications. *Materials*. 2020. https://doi.org/10.3390/ma13225236.
5. Pradeep NB, Hegde MMR, Manjunath Patel GC, Giasin K, Pimenov DY, Wojciechowski S. Synthesis and characterization of mechanically alloyed nanostructured ternary titanium based alloy for bio-medical applications. *J Mater Res Technol*. 2022;16:88–101. https://doi.org/10.1016/j.jmrt.2021.11.101.
6. Straumal B, Korneva A, Zieęba P. Phase transitions in metallic alloys driven by the high pressure torsion. *Arch Civ Mech Eng*. 2014;14:242–9. https://doi.org/10.1016/j.acme.2013.07.002.
7. Dong D, Xu H, Zhu D, Wang G, He Q, Lin J. Microstructure and mechanical properties of TiC/Ti matrix composites and Ti-48Al-2Cr-2Nb alloy joints brazed with Ti-28Ni eutectic filler alloy. *Arch Civ Mech Eng*. 2019;19:1259–67. https://doi.org/10.1016/j.acme.2019.07.005.
8. Fashu S, Lototskyy M, Davids MW, Pickering L, Linkov V, Tai S, Renheng T, Fangming X, Fursikov PV, Tarasov BP. A review on crucibles for induction melting of titanium alloys. *Mater Des*. 2020;186:108295. https://doi.org/10.1016/j.matdes.2019.108295.
9. Gupta NK, Somani N, Prakash C, Singh R, Walia AS, Singh S, Pruncu CI. Revealing the WEDM process parameters for the machining of pure and heat-treated titanium (Ti-6Al-4V) alloy. *Materials*. 2021. https://doi.org/10.3390/ma14092292.
10. Kopec M, Brodecki A, Szczęsny G, Kowalewski ZL. Microstructural analysis of fractured orthopedic implants. *Materials*. 2021. https://doi.org/10.3390/ma14092209.
11. Dutta Majumdar J, Manna I. Laser surface engineering of titanium and its alloys for improved wear, corrosion and high-temperature oxidation resistance. Sawston: Woodhead Publishing; 2015. p. 483–521.

12. Su C, Yu H, Wang Z, Yang J, Zeng X. Controlling the tensile and fatigue properties of selective laser melted Ti-6Al-4V alloy by post treatment. *J Alloys Compd.* 2021;857:157552. https://doi.org/10.1016/j.jallcom.2020.157552.
13. Hémery S, Stinville J-C. Microstructural and load hold effects on small fatigue crack growth in $\alpha+\beta$ dual phase Ti alloys. *Int J Fatigue.* 2021. https://doi.org/10.1016/j.ijfatigue.2021.106699.
14. Korkmaz ME, Gupta MK, Waqar S, Kuntoğlu M, Krolczyk GM, Maruda RW, Pimenov DY. A short review on thermal treatments of titanium & nickel based alloys processed by selective laser melting. *J Mater Res Technol.* 2022;16:1090-101. https://doi.org/10.1016/j.jmrt.2021.12.061.
15. Józwik J, Ostrowski D, Milczarczyk R, Krolczyk GM. Analysis of relation between the 3D printer laser beam power and the surface morphology properties in Ti-6Al-4V titanium alloy parts. *J Braz Soc Mech Sci Eng.* 2018;40:215. https://doi.org/10.1007/s40430-018-1144-2.
16. Yaşar N, Korkmaz ME, Gupta MK, Boy M, Günay M. A novel method for improving drilling performance of CFRP/Ti6AL4V stacked materials. *Int J Adv Manuf Technol.* 2021;117:653-73. https://doi.org/10.1007/s00170-021-07758-0.
17. Mia M, Gupta MK, Lozano JA, Carou D, Pimenov DY, Królczyk G, Khan AM, Dhar NR. Multi-objective optimization and life cycle assessment of eco-friendly cryogenic N2 assisted turning of Ti-6Al-4V. *J Clean Prod.* 2019;210:121-33. https://doi.org/10.1016/j.jclepro.2018.10.334.
18. Singla AK, Singh J, Sharma VS, Gupta MK, Song Q, Rozumek D, Krolczyk GM. Impact of cryogenic treatment on HCF and FCP performance of β-solution treated Ti-6Al-4V ELI biomaterial. *Materials.* 2020. https://doi.org/10.3390/ma13030500.
19. Garbiec D, Siwak P, Mróz A. Effect of compaction pressure and heating rate on microstructure and mechanical properties of spark plasma sintered Ti6Al4V alloy. *Arch Civ Mech Eng.* 2016;16:702-7. https://doi.org/10.1016/j.acme.2016.04.009.
20. Krolczyk G, Sedmak A, Kumar U, Chattopadhyaya S, Das AK, Pramanik A. Study of heat-affected zone and mechanical properties of Nd-YAG laser welding process of thin titanium alloy sheet. *Nat Resour Eng.* 2016;1:51-8. https://doi.org/10.1080/17580930.2016.1168415.
21. Chauhan SR, Dass K. Dry sliding wear behaviour of titanium (Grade 5) alloy by using response surface methodology. *Adv Tribol.* 2013. https://doi.org/10.1155/2013/272106.
22. Ł picka M, Gradzka-Dahlke M. Surface modification of Ti6Al4V titanium alloy for biomedical applications and its effect on tribological performance –a review. *Rev Adv Mater Sci.* 2016;46:86-103.

23. Sreesha RB, Kumar D, Chandraker S, Agrawal A. Room temperature sliding wear behavior of Ti6Al4V: a review. *AIP Conf Proc.* 2021. https://doi.org/10.1063/5.0049962.

24. Kaur S, Ghadirinejad K, Oskouei RH. An overview on the tribological performance of titanium alloys with surface modifications for biomedical applications. *Lubricants.* 2019. https://doi.org/10.3390/lubricants7080065.

25. Jozwik J. Evaluation of tribological properties and condition of Ti6Al4V titanium alloy surface. *Teh Vjesn TechGaz.* 2018. https://doi.org/10.17559/TV-20160521145125.

26. Krolczyk GM, Nieslony P, Legutko S. Determination of tool life and research wear during duplex stainless steel turning. *Arch Civ Mech Eng.* 2015;15:347–54. https://doi.org/10.1016/j.acme.2014.09.001.

27. Nabhani F. Wear mechanisms of ultra-hard cutting tools materials. *J Mater Process Technol.* 2001;115:402–12. https://doi.org/10.1016/S0924-0136(01)00851-2.

28. Kuntoğlu M, Sağlam H. Investigation of progressive tool wear for determining of optimized machining parameters in turning. *Measurement.* 2019;140:427–36. https://doi.org/10.1016/j.measurement.2019.04.022.

29. Salur E, Aslan A, Kuntoglu M, Gunes A, Sahin OS. Experimental study and analysis of machinability characteristics of metal matrix composites during drilling. *Compos Part B Eng.* 2019;166:401–13. https://doi.org/10.1016/j.compositesb.2019.06.048.

30. Salur E, Kuntoğlu M, Aslan A, Pimenov DY. The effects of MQL and dry environments on tool wear, cutting temperature, and power consumption during end milling of AISI 1040 steel. *Metals (Basel).* 2021;11:1674.

31. Kuntoğlu M, Sağlam H. ANOVA and fuzzy rule based evaluation and estimation of flank wear, temperature and acoustic emission in turning. *CIRP J Manuf Sci Technol.* 2021;35:589–603. https://doi.org/10.1016/j.cirpj.2021.07.011.

32. Kuntoğlu M, Sağlam H. Investigation of signal behaviors for sensor fusion with tool condition monitoring system in turning. *Measurement.* 2021;173:108582. https://doi.org/10.1016/j.measurement.2020.108582.

33. Grzesik W, Małecka J, Zalisz Z, Zak K, Niesłony P. Investigation of friction and wear mechanisms of TiAlV coated carbide against Ti6Al4V titanium alloy using pin-on-disc tribometer. *Arch Mech Eng.* 2016;63:113–27. https://doi.org/10.1515/meceng-2016-0006.

34. Astakhov VP. Tribology of cutting tools. *Tribol Manuf Technol.* 2012. https://doi.org/10.1007/978-3-642-31683-8_1.

35. Ghazali MF, Abdullah MM, Abd Rahim SZ, Gondro J, Pietrusiewicz P, Garus S, Stachowiak T, Sandu AV, Mohd Tahir MF, Korkmaz ME, Os-

man MS. Tool wear and surface evaluation in drilling fly ash geopolymer using HSS, HSS-Co, and HSS-TiN cutting tools. *Materials*. 2021. https://doi.org/10.3390/ma14092277.

36. Korkmaz ME, Gupta MK, Boy M, Yaşar N, Krolczyk GM, Günay M. Influence of duplex jets MQL and nano-MQL cooling system on machining performance of Nimonic 80A. *J Manuf Process*. 2021;69:112–24. https://doi.org/10.1016/j.jmapro.2021.06.001.
37. Wojciechowski S, Chwalczuk T, Twardowski P, Krolczyk GM. Modeling of cutter displacements during ball end milling of inclined surfaces. *Arch Civ Mech Eng*. 2015;15:798–805. https://doi.org/10.1016/j.acme.2015.06.008.
38. Sharma S, Singh J, Gupta MK, Mia M, Dwivedi SP, Saxena A, Chattopadhyaya S, Singh R, Pimenov DY, Korkmaz ME. Investigation on mechanical, tribological and microstructural properties of Al–Mg–Si–T6/SiC/muscovite-hybrid metal-matrix composites for high strength applications. *J Mater Res Technol*. 2021;12:1564–81. https://doi.org/10.1016/j.jmrt.2021.03.095.
39. Korkmaz ME, Yaşar N, Günay M. Numerical and experimental investigation of cutting forces in turning of Nimonic 80A superalloy. *Eng Sci Technol an Int J*. 2020;23:664–73. https://doi.org/10.1016/j.jestch.2020.02.001.
40. Korkmaz ME, Günay M. Experimental and statistical analysis on machinability of nimonic80A superalloy with PVD coated carbide. *Sigma J Eng Nat Sci*. 2018;36:1141–52.
41. Korkmaz ME. Verification of Johnson-Cook parameters of ferritic stainless steel by drilling process: experimental and finite element simulations. *J Mater Res Technol*. 2020;9:6322–30. https://doi.org/10.1016/j.jmrt.2020.03.045.
42. Günay M, Korkmaz ME, Yaşar N. Performance analysis of coated carbide tool in turning of Nimonic 80A superalloy under different cutting environments. *J Manuf Process*. 2020;56:678–87. https://doi.org/10.1016/j.jmapro.2020.05.031.
43. Inagaki I, Takechi T, Shirai Y, Ariyasu N. Application and features of titanium for the aerospace industry, nippon steel sumitomo. *Met Tech Rep*. 2014;106:22–7.
44. Murr LE, Quinones SA, Gaytan SM, Lopez MI, Rodela A, Martinez EY, Hernandez DH, Martinez E, Medina F, Wicker RB. Microstructure and mechanical behavior of Ti–6Al–4V produced by rapid-layer manufacturing, for biomedical applications. *J Mech Behav Biomed Mater*. 2009;2:20–32. https://doi.org/10.1016/j.jmbbm.2008.05.004.
45. Trevisan F, Calignano F, Aversa A, Marchese G, Lombardi M, Biamino S, Ugues D, Manfredi D. Additive manufacturing of titanium alloys in the biomedical field: processes, properties and applications. *J Appl Biomater Funct Mater*. 2018;16:57–67. https://doi.org/10.5301/jabfm.5000371.

46. Titanium Facts & Characteristics: Manufacturers Guide | Ulbrich, (n.d.).
47. Pradhan S, Singh S, Prakash C, Królczyk G, Pramanik A, Pruncu CI. Investigation of machining characteristics of hard-to-machine Ti-6Al-4V-ELI alloy for biomedical applications. *J Mater Res Technol.* 2019;8:4849-62. https://doi.org/10.1016/j.jmrt.2019.08.027.
48. Mouritz AP. Titanium alloys for aerospace structures and engines. *Introduction to aerospace materials.* Sawston: Woodhead Publishing; 2012. p. 202-23.
49. Zhou Z, Fei Y, Lai M, Kou H, Chang H, Shang G, Zhu Z, Li J, Zhou L. Microstructure and mechanical properties of new metastable β type titanium alloy. *Trans Nonferrous Met Soc China.* 2010;20:2253-8. https://doi.org/10.1016/S1003-6326(10)60454-8.
50. Singh SK, Muneshwar P, Kumar KN, Pant B, Sreekumar K, Sinha PP. Development and characterization of Ti5Al2.5Sn-ELI alloy hemispherical domes for high-pressure cold helium tanks. *Mater Sci Forum.* 2012;710:113-8. https://doi.org/10.4028/www.scientific.net/MSF.710.113.
51. Williams JC, Boyer RR. Opportunities and issues in the application of titanium alloys for aerospace components. *Metals.* 2020. https://doi.org/10.3390/met10060705.
52. Pitchi CS, Priyadarshini A, Sana G, Narala SKR. A review on alloy composition and synthesis of β-titanium alloys for biomedical applications. *Mater Today Proc.* 2020;26:3297-304. https://doi.org/10.1016/j.matpr.2020.02.468.
53. Antunes RA, Salvador CAF, de Oliveira MCL. Materials selection of optimized titanium alloys for aircraft applications. *Mater Res.* 2018. https://doi.org/10.1590/1980-5373-mr-2017-0979.
54. Fan H, Liu Y, Yang S. Martensite decomposition during post-heat treatments and the aging response of near-α Ti-6Al-2Sn-4Zr-2Mo (Ti-6242) titanium alloy processed by selective laser melting (SLM). *J Micromech Mol Phys.* 2021. https://doi.org/10.1142/S2424913020500186.
55. Cotton JD, Briggs RD, Boyer RR, Tamirisakandala S, Russo P, Shchetnikov N, Fanning JC. State of the art in beta titanium alloys for airframe applications. *JOM.* 2015;67:1281-303. https://doi.org/10.1007/s11837-015-1442-4.
56. Ouyang P, Dong H, He X, Cai X, Wang Y, Li J, Li H, Jin Z. Hydromechanical mechanism behind the effect of pore size of porous titanium scaffolds on osteoblast response and bone ingrowth. *Mater Des.* 2019;183:108151. https://doi.org/10.1016/j.matdes.2019.108151.
57. Geetha M, Singh AK, Asokamani R, Gogia AK. Ti based biomaterials, the ultimate choice for orthopaedic implants—a review. *Prog Mater Sci.* 2009;54:397-425. https://doi.org/10.1016/j.pmatsci.2008.06.004.

58. Demirsöz R, Korkmaz ME, Gupta MK, Collado AG, Krolczyk GM. Erosion characteristics on surface texture of additively manufactured AlSi10Mg alloy in SiO quartz added slurry environment. *Rapid Prototyp J.* 2021. https://doi.org/10.1108/RPJ-10-2021-0283.

59. Demirsöz R, Polat R, Türk A, Erdoğan G. Investigation of erosive wear behavior of granulated blast furnace slag on hard coated and uncoated steels. *J Fac Eng Archit Gazi Univ.* 2019;34:103–13. https://doi.org/10.17341/gazimmfd.416467.

60. Wood RJ, Ramkumar P, Wang L, Wang TJ, Nelson K, Yamaguchi ES, Harrison JJ, Powrie HE, Otin N. Electrostatic monitoring of the effects of carbon black on lubricated steel/steel sliding contacts. In: Dowson D, Priest M, Dalmaz G, Lubrecht AA, editors. *Life cycle tribol.* New York: Elsevier; 2005. p. 109–21.

61. Molinari A, Straffelini G, Tesi B, Bacci T. Dry sliding wear mechanisms of the Ti6A14V alloy. *Wear.* 1997;208:105-12. https://doi.org/10.1016/S0043-1648(96)07454-6.

62. Hager CH, Sanders JH, Sharma S. Effect of high temperature on the characterization of fretting wear regimes at Ti6Al4V interfaces. *Wear.* 2006;260:493–508. https://doi.org/10.1016/j.wear.2005.03.011.

63. Straffelini G, Molinari A. Dry sliding wear of Ti-6Al-4V alloy as influenced by the counterface and sliding conditions. *Wear.* 1999;236:328–38. https://doi.org/10.1016/S0043-1648(99)00288-4.

64. Alam MO, Haseeb ASMA. Response of Ti-6Al-4V and Ti-24Al-11NB alloys to dry sliding wear against hardened steel. *Tribol Int.* 2002;35:357-62. https://doi.org/10.1016/S0301-679X(02)00015-4.

65. Qiu M, Zhang Y, Zhu J, Yang J. Dry friction characteristics of Ti-6Al-4V alloy under high sliding velocity. *J Wuhan Univ Technol Mater Sci Ed.* 2007;22:582–5. https://doi.org/10.1007/s11595-006-4582-0.

66. Cui XH, Mao YS, Wei MX, Wang SQ. Wear characteristics of Ti-6Al-4V Alloy at 20–400°C. *Tribol Trans.* 2012;55:185-90. https://doi.org/10.1080/10402004.2011.647387.

67. Fellah M, Labaïz M, Assala O, Dekhil L, Taleb A, Rezag H, Iost A. Tribological behavior of Ti-6Al-4V and Ti-6Al-7Nb alloys for total hip prosthesis. *Adv Tribol.* 2014. https://doi.org/10.1155/2014/451387.

68. Ashok Raj J, Pottirayil A, Kailas SV. Dry sliding wear behavior of Ti-6Al-4V pin against ss316l disk at constant contact pressure. *J Tribol.* 2017. https://doi.org/10.1115/1.4033363.

69. Liu Y, Yang D, He S, Ye Z. Dry sliding wear of Ti-6Al-4V alloy at low temperature in vacuum Bt—protection of materials and structures from the space environment. Dordrecht: Springer; 2006. p. 309–16.

70. Conradi M, Kocijan A, Klobčar D, Podgornik B. Tribological response of laser-textured Ti6Al4V alloy under dry conditions and lubricated with Hank's solution. *Tribol Int.* 2021. https://doi.org/10.1016/j.triboint.2021.107049.

71. Mao YS, Wang L, Chen KM, Wang SQ, Cui XH. Tribo-layer and its role in dry sliding wear of Ti-6Al-4V alloy. *Wear.* 2013;297:1032–9. https://doi.org/10.1016/j.wear.2012.11.063.

72. Jozwik J. Evaluation of tribological properties and condition of TI6AL4V titanium alloy surface. *Teh Vjesn.* 2018;25:170-5. https://doi.org/10.17559/TV-20160521145125.

73. Wang L, Zhang QY, Li XX, Cui XH, Wang SQ. Severe-to-mild wear transition of titanium alloys as a function of temperature. *Tribol Lett.* 2014;53:511–20. https://doi.org/10.1007/s11249-013-0289-5.

74. Feng C, Khan TI. The effect of quenching medium on the wear behaviour of a Ti-6Al-4V alloy. *J Mater Sci.* 2008;43:788–92. https://doi.org/10.1007/s10853-007-2298-y.

75. Yang Y, Zhang C, Dai Y, Luo J. Tribological properties of titanium alloys under lubrication of SEE oil and aqueous solutions. *Tribol Int.* 2017;109:40–7. https://doi.org/10.1016/j.triboint.2016.11.040.

76. Luo Y, Yang L, Tian M. Influence of bio-lubricants on the tribological properties of Ti6Al4V alloy. *J Bionic Eng.* 2013;10:84–9. https://doi.org/10.1016/S1672-6529(13)60207-8.

77. Cvijović-Alagić I, Cvijović Z, Mitrović S, Rakin M, Veljović D, Babić M. Tribological behaviour of orthopaedic Ti-13Nb-13Zr and Ti-6Al-4V alloys. *Tribol Lett.* 2010;40:59–70. https://doi.org/10.1007/s11249-010-9639-8.

78. Chetan BC, Behera S, Ghosh PV. Wear behavior of PVD TiN coated carbide inserts during machining of Nimonic 90 and Ti6Al4V superalloys under dry and MQL conditions. *Ceram Int.* 2016;42:14873–85. https://doi.org/10.1016/j.ceramint.2016.06.123.

79. Liang X, Liu Z, Wang B. Physic-chemical analysis for high-temperature tribology of WC-6Co against Ti-6Al-4V by pin-on-disc method. *Tribol Int.* 2020;146:106242. https://doi.org/10.1016/j.triboint.2020.106242.

80. Yang Y, Zhang C, Wang Y, Dai Y, Luo J. Friction and wear performance of titanium alloy against tungsten carbide lubricated with phosphate ester. *Tribol Int.* 2016;95:27–34. https://doi.org/10.1016/j.triboint.2015.10.031.

81. Egaña A, Rech J, Arrazola PJ. Characterization of friction and heat partition coefficients during machining of a TiAl6V4 titanium alloy and a cemented carbide. *Tribol Trans.* 2012;55:665–76. https://doi.org/10.1080/10402004.2012.692007.

82. Courbon C, Pusavec F, Dumont F, Rech J, Kopac J. Tribology International Tribological behaviour of Ti6Al4V and Inconel718

under dry and cryogenic conditions—application to the context of machining with carbide tools. *Tribiology Int.* 2013;66:72–82. https://doi.org/10.1016/j.triboint.2013.04.010.

83. Krajewska-Spiewak J, Gawlik J. Effect of residual stresses in surface layer of nickel-based alloy—inconel 718 on the safety factor of construction BT—advances in manufacturing. In: Hamrol A, Ciszak O, Legutko S, Jurczyk M, editors. *Advances in manufacturing.* Cham: Springer International Publishing; 2018. p. 933–40.
84. Patil A. Tribological behavior of WC-CO carbide filled with solid lubricant in dry sliding. *Int Res J Eng Technol.* 2020;7:3975–80.
85. Jadhav PM, Kumar Reddy NS. Wear behavior of carbide tool coated with Yttria-stabilized zirconia nano particles. *IOP Conf Ser Mater Sci Eng.* 2018;346:12007. https://doi.org/10.1088/1757-899x/346/1/012007.
86. Niu QL, Zheng XH, Ming WW, Chen M. Friction and wear performance of titanium alloys against tungsten carbide under dry sliding and water lubrication. *Tribol Trans.* 2013;56:101–8. https://doi.org/10.1080/10402004.2012.729296.
87. Qu J, Blau PJ, Watkins TR, Cavin OB, Kulkarni NS. Friction and wear of titanium alloys sliding against metal, polymer, and ceramic counterfaces. *Wear.* 2005;258:1348–56. https://doi.org/10.1016/j.wear.2004.09.062.
88. Xuedong W, Dapu W, Shengrong Y, Qunji X. Tribochemical investigation of tungsten carbide/titanium alloy tribo-couples under aqueous lubrication. *Wear.* 2000;237:28–32. https://doi.org/10.1016/S0043-1648(99)00288-4.
89. Cadena NL, Cue-Sampedro R, Siller HR, Arizmendi-Morquecho AM, Rivera-Solorio CI, Di-Nardo S. Study of PVD AlCrN coating for reducing carbide cutting tool deterioration in the machining of titanium alloys. *Materials (Basel).* 2013;6:2143–54. https://doi.org/10.3390/ma6062143.
90. Mo JL, Zhu MH, Lei B, Leng YX, Huang N. Comparison of tribological behaviours of AlCrN and TiAlN coatings—deposited by physical vapor deposition. *Wear.* 2007;263:1423–9. https://doi.org/10.1016/J.WEAR.2007.01.051.
91. Medina N, Miguel V, Martínez A, Coello J, Manjabacas MC. Methodology to evaluate the tribology of pairs coated CW based tools and Ti6Al4V alloy. *Procedia Manuf.* 2017;13:631–8. https://doi.org/10.1016/j.promfg.2017.09.132.
92. El-Tayeb NSM, Yap TC, Venkatesh VC, Brevern PV. Modeling of cryogenic frictional behaviour of titanium alloys using response surface methodology approach. *Mater Des.* 2009;30:4023–34. https://doi.org/10.1016/j.matdes.2009.05.020.
93. Quan X, Xie H, Xu X, Tang J. Study on the enhanced tribological performance for titanium alloys by PEG oil/Zn-nanoparticles. *Mater Res*

Express. 2020. https://doi.org/10.1088/2053-1591/abcd59.

94. Allen C, Bloyce A, Bell T. Sliding wear behaviour of ion implanted ultra high molecular weight polyethylene against a surface modified titanium alloy Ti-6Al-4V. *Tribol Int*. 1996;29:527–34. https://doi.org/10.1016/0301-679X(95)00116-L.
95. Yilbas BS, Sahin AZ, Al-Garni AZ, Said SAM, Ahmed Z, Abdulaleem BJ, Sami M. Plasma nitriding of Ti-6Al-4V alloy to improve some tribological properties. *Surf Coatings Technol*. 1996;80:287–92. https://doi.org/10.1016/0257-8972(95)02472-7.
96. Oñate JI, Alonso F, García A. Improvement of tribological properties by ion implantation. *Thin Solid Films*. 1998;317:471–6. https://doi.org/10.1016/S0040-6090(97)00564-6.
97. Itoh Y, Itoh A, Azuma H, Hioki T. Improving the tribological properties of Ti-6Al-4V alloy by nitrogen-ion implantation. *Surf Coatings Technol*. 1999;111:172–6. https://doi.org/10.1016/S0257-8972(98)00728-2.
98. Vakili-Azghandi M, Roknian M, Szpunar JA, Mousavizade SM. Surface modification of pure titanium via friction stir processing: microstructure evolution and dry sliding wear performance. *J Alloys Compd*. 2020;816:152557. https://doi.org/10.1016/j.jallcom.2019.152557.
99. Guleryuz H, Cimenoglu H. Surface modification of a Ti-6Al-4V alloy by thermal oxidation. *Surf Coatings Technol*. 2005;192:164–70. https://doi.org/10.1016/j.surfcoat.2004.05.046.
100. Pratap T, Patra K. Mechanical micro-texturing of Ti-6Al-4V surfaces for improved wettability and bio-tribological performances. *Surf Coatings Technol*. 2018;349:71–81. https://doi.org/10.1016/j.surfcoat.2018.05.056.
101. Prakash C, Singh S, Pruncu CI, Mishra V, Królczyk G, Pimenov DY, Pramanik A. Surface modification of Ti-6Al-4V alloy by electrical discharge coating process using partially sintered Ti-Nb electrode. *Materials*. 2019. https://doi.org/10.3390/ma12030461.
102. Ghosh S, Choudhury D, Roy T, Bin Mamat A, Masjuki HH, Pingguan-Murphy B. Tribological investigation of diamond-like carbon coated micro-dimpled surface under bovine serum and osteoarthritis oriented synovial fluid. *Sci Technol Adv Mater*. 2015;16:1–11. https://doi.org/10.1088/1468-6996/16/3/035002.
103. Kang J, Wang M, Yue W, Fu Z, Zhu L, She D, Wang C. Tribological behavior of titanium alloy treated by nitriding and surface texturing composite technology. *Materials (Basel)*. 2019. https://doi.org/10.3390/ma12020301.
104. Singh R, Dureja JS, Dogra M, Gupta MK, Mia M, Song Q. Wear behavior of textured tools under graphene-assisted minimum quantity lubrica-

tion system in machining Ti-6Al-4V alloy. *Tribol Int.* 2020;145:106183. https://doi.org/10.1016/j.triboint.2020.106183.

105. Hsu CS, Li Q. Surface modification of Ti64 through hydrothermal treatment in urea solutions. *Mater Lett.* 2018;216:299-302. https://doi.org/10.1016/j.matlet.2018.01.114.
106. Datta S, Das M, Balla VK, Bodhak S, Murugesan VK. Mechanical, wear, corrosion and biological properties of arc deposited titanium nitride coatings. *Surf Coatings Technol.* 2018;344:214-22. https://doi.org/10.1016/j.surfcoat.2018.03.019.
107. Danişman D, Odabas M. The effect of coatings on the wear behavior of Ti6Al4V alloy used in biomedical applications. *IOP Conf Ser Mater Sci Eng.* 2018;295:12. https://doi.org/10.1088/1757-899X/295/1/012044.
108. Shao M, Wang W, Yang H, Zhang X, He X. Preparation of wear-resistant coating on Ti6Al4V alloy by cold spraying and plasma electrolytic oxidation. *Coatings.* 2021. https://doi.org/10.3390/coatings11111288.
109. Roy MR, Ramanaiah N, Rao BSK. Effect of Hank' s solution on sliding wear behaviour of Cr_3C_2-NiCr coated Ti6Al4V alloy. *Int J Mech Eng.* 2017;1:304-9.
110. Revankar GD, Shetty R, Rao SS, Gaitonde VN. Wear resistance enhancement of titanium alloy (Ti-6Al-4V) by ball burnishing process. *J Mater Res Technol.* 2017;6:13-32. https://doi.org/10.1016/j.jmrt.2016.03.007.

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv —Machine translation. Verify with original.