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EDITED BY
Chao Yang,
South China University of Technology, China

REVIEWED BY
Xuming Zha,
Jimei University, China
Ajay Kumar,
JECRC University, India

*CORRESPONDENCE
Egemen Avcu,
avcuegemen@gmail.com
Mustafa Armağan,
mustafaarmagan@hotmail.com.tr

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Advances in improving tribological performance of titanium alloys and titanium matrix composites for biomedical applications: a critical review

Eray Abakay[1], Mustafa Armağan[2]*, Yasemin Yıldıran Avcu[3], Mert Guney[4,5], B. F. Yousif[6] and Egemen Avcu[3,7]*

[1]Department of Metallurgy and Materials Engineering, Sakarya University, Sakarya, Türkiye, [2]Department of Mechanical Engineering, Istanbul Medeniyet University, Istanbul, Türkiye, [3]Department of Mechanical Engineering, Kocaeli University, Kocaeli, Türkiye, [4]The Environment and Resource Efficiency Cluster (EREC), Nazarbayev University, Nur-Sultan, Kazakhstan, [5]Department of Civil and Environmental Engineering, Nazarbayev University, Nur-Sultan, Kazakhstan, [6]School of Engineering, University of Southern Queensland, Toowoomba, QLD, Australia, [7]Department of Machine and Metal Technologies, Kocaeli University, Kocaeli, Türkiye

Titanium (Ti) alloys have been widely used in biomedical applications due to their superior mechanical, physical, and surface properties, while improving their tribological properties is critical to widening their biomedical applications in the current era. The present review examines the recent progress made in enhancing the tribological performance of titanium alloys and titanium matrix composites for biomedical purposes. It specifically focuses on the progress made in biomedical coatings, mechanical surface treatment, and developing titanium matrix composites in terms of their processing, tribological testing conditions, and characterization. Despite thorough investigations, the specific testing procedures for evaluating the friction and wear properties of the alloy and/or biomedical component are still uncertain. The majority of researchers have selected test methods and parameters based on previous studies or their own knowledge, but there is a scarcity of studies that incorporate limb-specific tribological tests that consider the distinct kinematic and biological structure of human limbs. Since advanced microscopy has great potential in this field, a variety of advanced characterization techniques have been used to reveal the relationship between microstructural and tribological properties. Many coating-based strategies have been developed using anodizing, PEO, VD, PVD, nitriding, thermal spray, sol-gel, and laser cladding, however; composition and processing parameters are crucial to improving tribological behaviour. Reinforcing component type, amount, and distribution has dominated Ti matrix composite research. Ti grade 2 and Ti6Al4V alloy has been the most widely used matrix, while various reinforcements, including TiC, Al_2O_3, TiB, hydroxyapatite, Si_3N_4, NbC, ZrO_2 have been incorporated to enhance tribological performance of Ti matrix. Mechanical surface treatments improve biomedical Ti alloys' tribological performance, which is advantageous due to their ease of application. The implementation of machine learning methods, such as artificial neural networks, regression, and fuzzy logic, is anticipated to make a substantial contribution to the field due to their ability to provide cost-effective and accurate results. The microstructural and surface features of biomedical Ti alloys directly affect their tribological properties, so image processing strategies using deep learning can help researchers optimize these properties for optimal performance.

KEYWORDS

mechanical surface treatment, coatings, Titanium alloy, biological properties, coefficient of friction, wear behavior, wear mechanisms, microstructural properties

1 Introduction

The selection of material and manufacturing methods for biomedical implants is crucial when considering the specific locations and movement conditions of structures like joints and bones in the human body. Increasing hardness and improving the wear properties of implants (Somasundaram Prasadh et al., 2021) could extend their service life (Kumar et al., 2021). This is especially pertinent when considering implants such as in knees and arms, as they experience high levels of stress and deterioration. Furthermore, the failure of an implant may result in a more extensive revision surgery and may potentially lead to complications such as bone loss and fractures. Regrettably, such cases lead to additional financial strain on both patients and the national healthcare systems due to the expenses associated with treatment (Sousa et al., 2022). The field of understanding tribological behaviour of biomaterials, particularly implants, aims to maintain friction and wear under the designed conditions by testing interacting surfaces in relative motion.

Titanium (Ti) and its alloys remain as preferred materials for implant production due to their superior properties. Despite their uses in a great variety of applications (briefly outlined in the following section), certain properties of Ti alloys such as low wear resistance, relatively low fatigue strength, and hardness may restrict their use, particularly if they are in contact with hard components under cycling loading (Kumar et al., 2018; Wang et al., 2019). Poor wear (Avila et al., 2021; Gonçalves et al., 2023) and corrosion behaviour of Ti alloys and their bioinert surfaces may slow down *in vivo* osseointegration (Avila et al., 2021; Sousa et al., 2021b). Moreover, inadequate tribocorrosion resistance (Sousa et al., 2021b; Gonçalves et al., 2023) of load-bearing Ti alloys is a major concern due to its impact on the interaction between the implant and the surrounding tissue (Sousa et al., 2022). In light of these limitations, researchers are exploring various methods for addressing the shortcomings of titanium alloys, which is the subject of the present review. It may be necessary to customize the surface properties of Ti alloys (such as roughness and surface topography) in order to enhance specific biological characteristics like osseointegration and antibacterial activity in biomedical applications, along with their tribological properties (Carreón et al., 2014). Thus, studies on improving tribological properties of titanium alloys have been an attractive field of research in the last decades. Consequently, a timely and thorough review is necessary to examine the progress made in enhancing the friction and wear properties of Ti alloys and Ti matrix composites for medical purposes.

This review provides an in-depth review of the tribological characteristics of titanium and titanium alloys. It accomplishes this by examining over 200 research articles published within the past 5 years. The paper provides a future perspective for researchers and industry by organising tribological testing, characterisation, and material production technologies in a systematic manner. The objective is to guarantee the progression of scientific knowledge in the field, the development of industrial applications, and the reproducibility of results. The present article is novel in its focus on the advancements in enhancing the tribological characteristics of Ti alloys, as outlined in Figure 1. It emphasizes the significant challenges and offers future directions in this field. A brief introduction of Ti alloys is presented by addressing their historical developments, applications, classifications, processing, and overall properties. Methods for testing and characterizing the tribological properties of titanium alloys are also briefly discussed. For each improvement strategy classified in Figure 1, final remarks and suggestions for future research are provided in the final section. Additionally, challenges and future research directions in investigating the tribological behavior of these materials are addressed.

2 A brief introduction to Titanium (Ti) alloys

Titanium and its alloys find extensive applications in aerospace, medical, marine, energy, chemical, petrochemical, and nuclear industries owing to their exceptional properties including high strength-to-weight ratio, corrosion resistance, biocompatibility, and ability to maintain performance at elevated temperatures (Carreón et al., 2014; Gospodinov et al., 2016; Ranjith Kumar et al., 2019; Petronić et al., 2020; Chattopadhyay et al., 2021). The widespread use of Ti alloys in the biomedical field is mainly due to its exceptional biocompatibility, excellent strength-to-density ratio, antibacterial properties, and remarkable resistance to corrosion (Qin et al., 2021; Ju et al., 2023; Soltani-Kordshuli et al., 2023). Consequently, it has a broad range of applications, including the implantation of hard tissue (Li Y. et al., 2024), joint replacements (Soltani-Kordshuli et al., 2023), screw implants (Zhang Y. et al., 2024), endoprostheses (Ranusa et al., 2022) and dental implants (Madeira et al., 2022). Nevertheless, their relatively low wear resistance reduces their service life (Ju et al., 2023; Lei et al., 2024; Li Y. et al., 2024; Siahpour et al., 2024) and restricts their applications where tribological contact is inevitable. Today, it is possible to achieve combined performance gains such as strength,

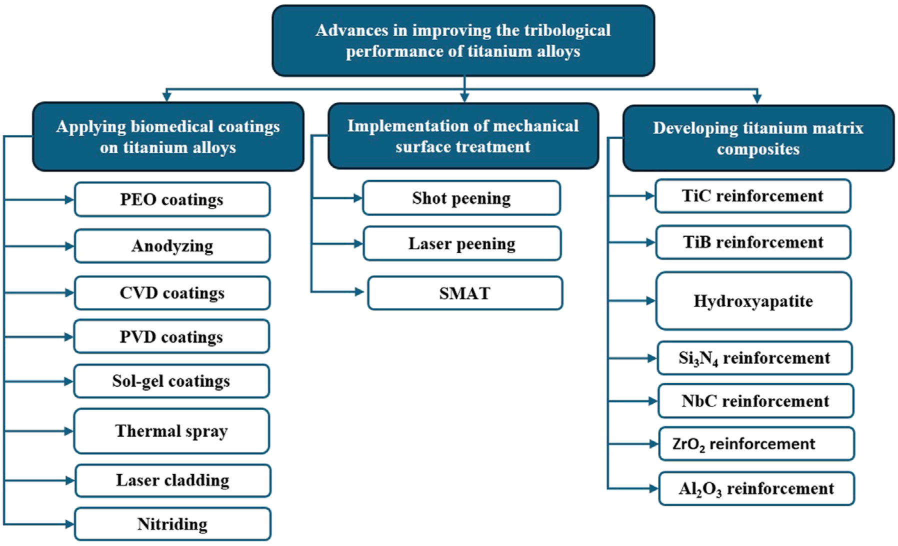

FIGURE 1
Most recent strategies for improving tribological properties of biomedical grade titanium alloys.

tribological, and hardness by applying additional methods such as coating and surface treatment to alloys. This section provides an overview of Ti alloys, focusing on their historical development, wide range of applications, systematic classification, and overall properties.

2.1 Historical development

Ti, formerly regards as a rare element (Liu et al., 2004), has now emerged as a highly important and widely used metal in a diverse range of applications from turbine blades (Ulutan and Ozel, 2011) to hip and knee replacements (Cui et al., 2011). It was discovered in England in 1791 by W. Gregor, a British clergyman and mineralogist (Liu et al., 2004; Nikiforov et al., 2014; Zhang et al., 2019), which was then named in 1795 by the German chemist Klaproth (Liu et al., 2004; Nikiforov et al., 2014). Ti is highly abundant in the earth's crust, ranking ninth among all elements. The vast majority of Ti exists in the form of insoluble oxides (Nikiforov et al., 2014; Gospodinov et al., 2016; Quinn et al., 2020). Therefore, it is necessary to extract it from minerals such as ilmenite, rutile, and anatase (Prasad et al., 2015; Quinn et al., 2020). In 1910, M.A. Hunter developed the Hunter process, which enabled the extraction of Ti from minerals. However, this method was not suitable for large-scale extraction of Ti. W. Kroll subsequently pioneered the Kroll process, which facilitated the efficient extraction and utilization of Ti in diverse industries, beginning in 1936 (Bangera and D'Costa, 2015; Prasad et al., 2015). Subsequently, it has become one of the most appealing engineering materials, specifically to military applications, thus its usage has exponentially increased (Sonntag et al., 2015). In the early 1950s, Leventhal and Branemark introduced it as a promising material for biomedical applications because of its exceptional resistance to corrosion and compatibility with the human body. At present, Ti and its alloys are widely recognized as biomaterials because of their exceptional biological properties (e.g., strong corrosion resistance (Zhang and Chen, 2019), excellent biocompatibility (Liu et al., 2019), very good and fast osteointegration (Vasilescu et al., 2019)) and their high weight to strength ratio which also puts them among the most widely used biomaterials (Wang et al., 2014; Sonntag et al., 2015).

2.2 Applications

Ti is commonly alloyed with elements such as aluminum, vanadium, molybdenum, iron, niobium, and others to produce high-performance alloys with strong strength to weight ratio. For instance, titanium grades with comparable strength to high strength steel are approximately 45% lighter than steel (Ranjith Kumar et al., 2019). Due to its high chemical reactivity, it readily forms thin (5–6 nm) oxide layers on its surface when exposed to the atmosphere. This makes it highly resistant to corrosion in various environments, such as freshwater, seawater, aqua regia, chlorine, and many acids (Gospodinov et al., 2016; Chattopadhyay et al., 2021). It also has many outstanding properties including fatigue resistance (Chattopadhyay et al., 2021), low thermal conductivity (Wang et al., 2019), fracture toughness (Zhou et al., 2015), excellent high-temperature properties (Carreón et al., 2014; Wang et al., 2014; Kumar et al., 2018), and good biocompatibility (Petronić et al., 2020). Therefore, Ti and its alloys are highly demanded in aeronautics applications (e.g., spacecraft, missile, and aircraft components such as skeleton, skin, fasteners, engine elements, landing gears (Wang et al., 2019), and jet propulsion engines (Zhou et al., 2015)), biomedical applications (Wang et al., 2014) (e.g., cementless orthopedic prostheses, dental and trauma surgery implants such as plates, screws, and intramedullary nails), nuclear industry (Ranjith Kumar et al., 2019; Chattopadhyay et al., 2021), chemical industry (Gospodinov et al., 2016) (e.g., desalination units, heat exchanger systems, transuranic waste containers, seawater-cooled piping), energy industry

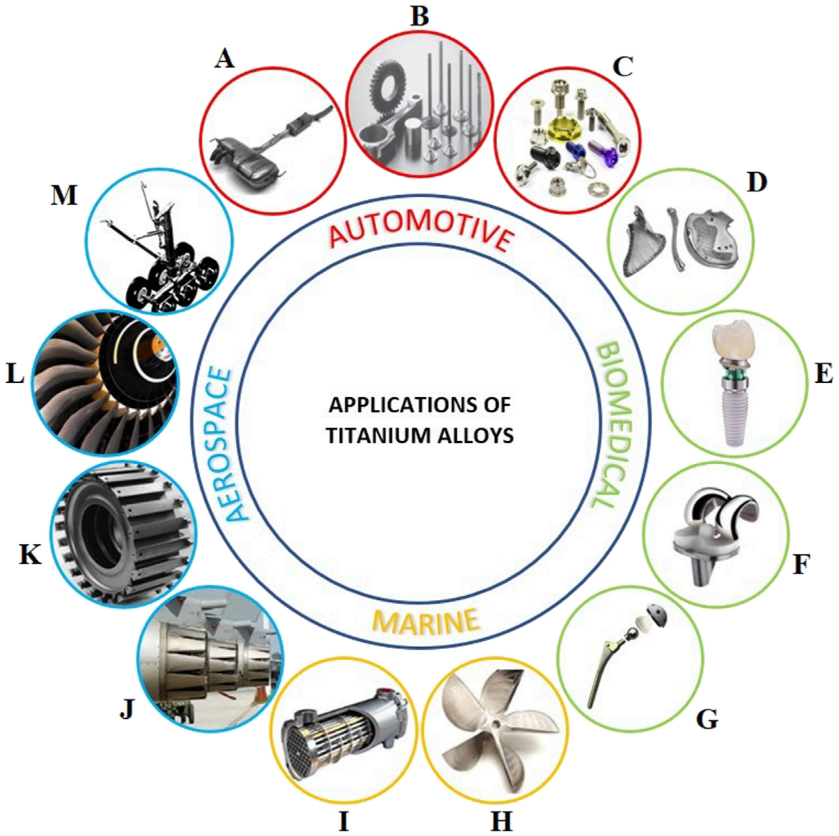

FIGURE 2
Example applications of Ti and its alloys in automotive: **(A)** exhaust system [adapted and modified from (Furuta, 2019)], **(B)** engine parts [adapted and modified from (Furuta, 2019)], and **(C)** fasteners [adapted and modified from (Gui et al., 2019)]; biomedical: **(D)** complex implants [adapted and modified from (Zhang et al., 2018)], **(E)** dental implant [adapted and modified from (Crosby, 2013)], **(F)** knee implant [adapted and modified from (Sáenz De Viteri and Fuentes, 2013)], **(G)** hip implant [adapted and modified from (Liu et al., 2004)]; marine: **(H)** propeller [adapted and modified from (Ranjith Kumar et al., 2019)], **(I)** heat exchanger [adapted and modified from (Ranjith Kumar et al., 2019)]; aerospace: **(J)** exhaust nozzle [adapted and modified from (Serra, 2008)], **(K)** fan disk [adapted and modified from (Tabie et al., 2020)], **(L)** fan blades [adapted and modified from (Lihui et al., 2014)], **(M)** main landing gear [adapted and modified from (Cotton et al., 2015)].

(Petronić et al., 2020) (e.g., hydrogen storage devices, heat exchanger systems (Ranjith Kumar et al., 2019)), automotive industry (Gospodinov et al., 2016; Chattopadhyay et al., 2021), military industry (Gospodinov et al., 2016; Wang et al., 2019), marine industry (Ranjith Kumar et al., 2019; Petronić et al., 2020; Chattopadhyay et al., 2021) (Figure 2).

2.3 Classification and processing

Ti alloys can be classified as α, near α, metastable β, or stable β according to their position in the β isomorphous phase diagram depending on the room temperature microstructure (Liu et al., 2004; Barriobero-Vila, 2015). Alloys can be classified based on their various phase types, which are determined by the different metallurgical structures they possess (Table 1). However, in practice, the utilization of all types of titanium alloys is infrequent. As a result, manufacturers have started categorizing alloys based on their economic worth (Table 2). Thus far, Ti6Al4V alloy is the most commonly used titanium alloy in dental, orthopedic, and tissue engineering applications among the various types of titanium alloys employed in the biomedical field (Hezil et al., 2022). Ti6Al4V alloy is expected to remain popular in the coming period due to its wide commercial availability and economic viability (Pushp et al., 2022; 2024e).

2.4 Overall properties

The chemical composition and microstructural features of Ti alloys have a significant impact on their physical, mechanical, and technological properties. The ultimate properties of these alloys are determined by the processing history and alloying, which allows for control over the properties (Liu et al., 2004; Barriobero-Vila, 2015). Briefly, solid solution strengthening, precipitation strengthening, transformation hardening, work hardening, and grain boundary strengthening are the main deformation mechanisms contributing to the improvement of mechanical properties through alloying and processing (Barriobero-Vila, 2015). Ti components are produced in various forms such as sheets, billets, foils, bars, tubes, and wires via traditional metalworking processes such as casting, forging, and machining (Crosby, 2013; Sefer, 2014)

TABLE 1 Titanium alloys classified by metallurgical structure with examples (Pushp et al., 2022).

Alloys	Examples
Alpha alloys	Commercially pure titanium- ASTM grade 1,2,3 and 4 Ti/Pd alloys – ASTM grade 7 and 11
Alpha + compound	Ti-2.5%Cu – IMI230
Near Alpha alloys	Ti-8%Al- 1%Mo-1%V
	Ti-6%Al-5%Zr-0.5%Mo-0.2%Si- IMI 685
	Ti-6%Al-4%Zr-2%Sn-2%Mo-0.08%Si
	Ti-5.5%Al-3%Zr-3.5%Sn-0.3%Mo-1%Nb-0.3%Si- IMI 829
	Ti-5.8%Al-3.5%Zr-4%Sn-0.5%Mo-0.7%Nb-0.3%Si- IMI 834
	Ti-6%Al-4%Zr-3%Sn-0.5%Mo-0.5%Si- Ti 1100
Alpha – Beta alloys	Ti-6%Al-4%V
	Ti-4%Al- 4%Mo-2%Sn-0.5%Si- IMI 151
	Ti-4%Al-4%Mo-4%Sn-0.5%Si
	Ti-6%Al-6%V-2%Sn
	Ti-6%Al-4%Zr-2%Sn-1%Mo
Metastable beta alloys	Ti-3Al-8V-6Cr-4Mo-4Zr- Beta C
	Ti-15V-3Cr-3Sn-3Al
	Ti-6V-6Mo-5.7Fe-2.7Al- TIMETAL 125

as well as via advanced processing methods such as additive manufacturing (AM) (Hao et al., 2016; Trevisan et al., 2018; Kaur and Singh, 2019; Zhang L. C. et al., 2020) and sinter plasma sintering (SPS) (Cordeiro and Barão, 2017; Zhang and Chen, 2019). Table 3 presents the mechanical properties of the most commonly used biomedical titanium alloys, with conventional and advanced processing methods (Niinomi, 1998; Biesiekierski et al., 2016; 2024a; Abd-Elaziem et al., 2024).

3 Tribological testing and characterization methods used for Ti alloys

Friction-induced degradation of biomedical materials leads to material loss and a decrease in mechanical performance, thereby compromising the functionality of these materials in critical applications (Stachowiak and Batchelor, 1993; Soltani-Kordshuli et al., 2023). Particles and ions detached from the material may accumulate in the surrounding tissues, resulting in inflammation and toxic reactions (Kim et al., 2019). This may detrimentally affect human health and general wellbeing, while also leading to substantial economic losses (Stachowiak and Batchelor, 1993; Bian et al., 2023). Given the increasing utilization of Ti alloys in diverse applications that require enhanced tribological performance, it is imperative for these alloys to conform to the prevailing international standards. Therefore, tribological testing and characterization processes are crucial in guaranteeing the design, production, quality, and performance of Ti alloys. Moreover, it is crucial to utilize the most appropriate tribological testing and characterization techniques in order to develop novel strategies (such as the development of functional alloys (Majzoobi et al., 2023), application of wear-resistant biocompatible coatings (Wang et al., 2023a), surface texturing (Niu et al., 2023), etc.) to address the aforementioned undesirable tribological properties of Ti alloys employed in biomedical applications (Ranusa et al., 2022).

3.1 Tribological testing

The widespread use of titanium and titanium alloys in the biomedical industry has resulted in the adoption of tribological tests in various conditions and designs. The diversity of human limbs can be comprehended by considering the kinematic and biological distinctions among them. Table 4 presents a summary of the tribological testing methods and associated parameters utilized to study tribological behaviour of titanium alloys in the last 5 years. Ball or pin relative motion wear test methods on disc or plate, which are widely used in traditional tribology science, are still current and applicable. The simplicity and effectiveness of these testing methods, combined with their economic benefits have made them a central area of interest and research among scholars.

The terms “ball-on-disk” (Figure 3A) and “pin-on-disk” (Figure 3B) describe a wear test system that involves using wear-resistant materials in the form of pins or balls. These elements are subjected to circular motion relative to the part being tested, with parameters such as speed, load, frequency, etc. being controlled. The ball-on-plate (Figure 3C) and pin-on-plate (Figure 3D) mechanisms operate on a similar principle, although the relative motion is linear. The parameter, referred to as either friction distance or stroke length, is defined as the predetermined length of the wear track in the experiments. The parameter, commonly set at 5 mm, has emerged as a pragmatic choice for researchers. While there is no clearly better choice for sliding speed, it can be suggested that reciprocating frequencies of 1, 2, and 5 Hz are more preferred. Intermediate values ranging from 1 to 20 N were found to be more favored for the applied load, as listed in Table 4.

Most researchers indicated a preference for their own experiences and the load values ascribed in the literature. Limited research has been conducted to ascertain load preferences by simulating forces and interactions between limbs (Ranusa et al., 2022; Bian et al., 2023; Zhang Y. et al., 2024). The friction element acting on the surface to be tested is predominantly composed of wear-resistant Si_3N_4 (Qin et al., 2021; Chen et al., 2024; Li Y. et al., 2024; Yu et al., 2024) and Al_2O_3 (Madeira et al., 2022; Bouchareb et al., 2024; Lei et al., 2024; Woźniak et al., 2024) ceramic-based materials. The continued popularity of the Ti-6Al-4V alloy (Kaur et al., 2019; Costa et al., 2022; Hezil et al., 2022; Ju et al., 2023), as previously mentioned, is demonstrated by the sustained interest of researchers in its efficacy. Dry friction tests (Kumar Murmu et al., 2024; Saier et al., 2024;

TABLE 2 Most commonly used titanium grades according to their economic worth (Titanium, 2024c).

ALLOY	C	N	O	H	Fe	Al	V	Others
Grade 2	<0.08	<0.03	<0.25	<0.015	<0.30	0.00	0.00	0.00
Grade 7	<0.08	<0.03	<0.25	<0.015	<0.30	0.00	0.00	0.2Pd
Grade 12	<0.08	<0.03	<0.25	<0.015	<0.30	0.00	0.00	0.3 Mo 0.8Ni
Grade 9 (3AL-2.5v)	<0.08	<0.03	<0.15	<0.015	<0.25	3.00	2.50	0.00
Grade 5 (6AL-4V)	<0.08	<0.05	<0.20	<0.015	<0.40	6.00	4.00	0.00
Grade 28 (3Al-2.5V-Ru)	<0.08	<0.03	<0.15	<0.015	<0.25	3.00	2.50	.11Ru
Grade 29 (6AL-4VELI- RU)	<0.08	<0.03	<0.13	<0.015	<0.25	6.00	4.00	.11Ru
6AL-6V-2Sn	<0.05	<0.04	<0.02	<0.015	0.65	6.00	6.00	2.0 Sn 0.75Cu
6AL-2Sn-4Zr-6 Mo	<0.04	<0.04	<0.15	<0.015	<0.15	6.00	0.00	2.0Sn 4.0Zr 6.0Mo
4.0Zr 4.0Mo Grade 19 (Beta-C)	<0.05	<0.03	<0.12	<0.02	<0.30	3.00	8.00	4.0Zr 4.0Nb 6.0Cr

Xu Y. et al., 2024; Zhang Q. et al., 2024) have been commonly used in studies where surface treatments have been applied to the alloy. On the other hand, studies focused on enhancing the production and performance of the alloy have predominantly utilized lubricants that mimic the properties of the human body. This phenomenon is purpose-driven and encompasses the specific field of study that the researcher concentrates on. To summarize, the comprehensive analyses demonstrate that the utilization of conventional and knowledge-based test designs and equipment remains applicable in the current era.

3.2 Tribological characterization

The tribological properties of Ti alloys, which are extensively studied during and after wear testing, can be categorized into three groups: evaluation of the coefficient of friction, analysis of surface topography after wear, and analysis of surface morphology after wear. The initial techniques employed are those of force-time recording and topographic survey. These techniques yield measurable and visible data, such as the level of deterioration, friction coefficient, roughness, wear rate, and other similar parameters. Afterwards, precise morphological imaging techniques are primarily used to comprehend the underlying wear mechanisms that contribute to the tribological behavior of the tested alloy. Finally, the analysis of the microstructure and crystal structure of the alloy resulting from wear is accomplished by employing techniques rooted in principles such as X-ray and electron diffraction.

The primary focus of nearly all tribological studies is to determine the amount of wear and the frictional coefficient that contribute to the performance of the titanium alloy in real-world practical applications. Figure 4 illustrates examples of the force-time based friction coefficient behaviour observed in wear tests. Figure 4A illustrates the development and stability of the friction coefficient on the surface of the Ti6Al4V alloy subjected to laser texturing and simultaneous nitriding processes under simulated body fluid (SBF) lubrication conditions (Wang et al., 2023a). The time-friction coefficient graph (Figure 4B) was employed to determine the stable and improved wear performance of all three coatings, depending on the type of TiN, CrN, and TiB_2 coatings applied to the same alloy by the RF magnetron sputter deposition method (Narayana and Saleem, 2024). Consequently, the graph formation allows for the interpretation of time- and distance-dependent behaviour.

Figures 5A,B illustrate the 3D sample findings of the wear marks, which were visualized by a laser confocal microscope and an optical profilometer, respectively. The three-dimensional structure of the wear marks formed as a result of the tribological test of the surface obtained by laser surface texturing and double glow plasma surface chromising process on Ti6Al4V alloy is presented (Figure 5A). With imaging, it is possible to rapidly make predictions about the wear comparison from the topographic image difference that occurs when the related work is unprocessed or when using a single processing method (Lei et al., 2024). The 3D image and cross-sectional geometry of the worn surface of the TiN coating, as previously described, are presented here (Narayana and Saleem, 2024). Furthermore, quantitative data such as wear rate and amount can be obtained from the analysis of cross-sectional geometries extracted from 3D wear images using a suite of software (Figure 5B). The wear rates of the powder metallurgically produced Ti-5Cu-xNb alloy at different Nb ratios under different frictional loads are shown in Figure 5C (Pandey et al., 2023a). Using a different approach, gravimetric wear amounts on pin and disc were calculated (Figure 5D) for the effect of fiber laser nitriding on Ti grade 2 and 5 alloys (Chan et al., 2017).

The morphological structures formed by wear tests are frequently examined by scanning electron microscopy (SEM) in order to gain insight into the processing mechanisms that give rise to them. This characterization approach plays a pivotal role in determining the success of newly developed titanium

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TABLE 3 Mechanical properties of the most widely used biomedical titanium alloys.

Titanium Alloy	Tensile strength (MPa)	Yield strength (MPa)	Elongation (%)	Modulus (GPa)	Hardness (HV)	Ref.
Pure Ti grade 1	240	170	24	102.7	127	Niinomi, 1998; Titanium, 2024b
Pure Ti grade 2	345	275	20	102.7	152	Niinomi, 1998; Titanium, 2024b
Pure Ti grade 3	450	380	18	103.4	183	Niinomi, 1998; Titanium, 2024b
Pure Ti grade 4	550	485	15	104.1	252	Niinomi, 1998; Titanium, 2024b
Ti–6Al–4V (annealed)	895–930	825–869	6–10	110–114	311	Niinomi, 1998; Titanium, 2024b
Ti–6Al–4V ELI (mill annealed)	860–965	795–875	10–15	101–110	303	Niinomi, 1998; Titanium, 2024b
Ti–6Al–7Nb	900–1050	880–950	8.1–15	114		Niinomi (1998)
Ti–5Al–2.5Fe	1020	895	15	112		Niinomi (1998)
Ti–5Al–1.5B	925–1080	820–930	15–17.0	110		Niinomi (1998)
Ti–35.3Nb–5.1Ta–7.1Zr	911	864	13.2	80		Niinomi (1998)
Ti–12Nb–5Fe	>1000	740	0.9	90	293	Biesiekierski et al. (2016)
Ti–7Ta–5Fe	1530	1250	1.2	110	430	Biesiekierski et al. (2016)
Ti–10Ta–4Fe	1450	1360	1.13	121	410	Biesiekierski et al. (2016)
Ti-42Nb (SLM)	683	674	11.7	60.5		Abd-Elaziem et al. (2024)
Ti-42Nb (LDED)	718	715	17.8	47.9		Abd-Elaziem et al. (2024)
Ti-27.5Nb	820	800	10	70		Abd-Elaziem et al. (2024)
Ti-7Mn	2130	1000	31	96		Abd-Elaziem et al. (2024)
Ti-13Nb-13Zr	996.19	794.63	5	65.28		Abd-Elaziem et al. (2024)
Ti-7Mn-10Nb	1842	842	34	87		Abd-Elaziem et al. (2024)
Ti-12Mo-6Zr-2Fe	931	897	12			Mechanical Properties, 2024a
Ti-15Mo	483	690	20			Mechanical Properties, 2024a

TABLE 4 Tribological testing methods and testing parameters for titanium alloys.

Year	Test Method	Friction distance/stroke length	Sliding speed/reciprocating frequency	Load	Friction pairs	Substrate	Ref.
2024	Ball-on-plate	15 mm	1 mm/s	20 N	Adult calf thighbones	Ti-6Al-4V alloy sheet	Zhang et al. (2024b)
2024	Ball-on flat	1 mm	5 Hz	20 N	Si_3N_4 ceramic	Ti-6Al-4V alloy sheet	Xu et al. (2024b)
2024	Ball-on-plate	6 mm	1 Hz	3, 6, 9 N	Al_2O_3 ceramic	Ti-6Al-4V ELI selected laser melting	Woźniak et al. (2024)
2024	Ball-on disk			2, 8, 16 N		HIPed near type Ti-15Mo alloys sintering	Toualbia et al. (2024)
2024	Ball-on-plate	5 mm	5 Hz	10, 25, 40 N	Al_2O_3 ceramic	Ti-6Al-4V alloy plate with annealing step	Siahpour et al. (2024)
2024	Ball-on disk	10, 15, 20 m	15 Hz	20 N	SiC	Ti-6Al-4V alloy sheet	Narayana and Saleem (2024)
2024	Ball-on disk		200 rpm	10 N	Al_2O_3 ceramic	Ti-6Al-4V alloy rod	Lei et al. (2024)
2024	Ball-on disk	5 mm	15 mm/s-5 and 10 Hz	2, 10, 20 N	Al_2O_3 ceramic	Ti-25Nb-25Zr alloy sintering	Hamadi et al. (2024)
2024	Ball-on disk		15 mm/s	2, 10, 20 N	Al_2O_3 ceramic	β-type Ti-alloys (Ti–25Nb-xZr)	Fellah et al. (2024)
2024	Ball-on-plate	5 mm	25 mm/s	2, 10, 20 N	Al_2O_3 ceramic	Ti50-Ni50 sintering	Bouchareb et al. (2024)
2023	Pin on plate	2 mm	1 Hz	1 N	Cortical bone	Ti-6Al-4V alloy plate	Wang et al. (2023b)
2023	Ball-on disk		31.4 mm/s	1.96 N	Si_3N_4 ceramic	Ti-6Al-4V alloy sheet	Wang et al. (2023a)
2023	Pin-on disk	5 mm	1 mm/s	10 N	PEEK pins	Ti–6Al–4V-ELI	Soltani-Kordshuli et al. (2023)
2023	Pin-on disk	4.147 km	550 rpm	18 N	Titanium Gr2	hardened AISI D2	Şirin et al. (2023)
2023	Ball-on disk	754 m	0.21 m/s	5, 10 N	AISI 51200 bearing steel	Ti-6Al-4V alloy sheet	Shen and Wang (2023)
2023	Ball-on disk					Ti–50Zr alloy additive manufacturing	Reger et al. (2023)
2023	Ball-on disk	5 mm	2 Hz	10 N	Zirconia	cPTi and Ti-6Al-4V alloy rods (annealed)	Pandey et al. (2023b)
2023	Ball-on-plate	5 mm	2 Hz	10, 15, 20 N	ZrO_2	Ti-5Cu-xNb sintering	Pandey et al. (2023a)
2023	Ball-on disk		480 rpm	24 N	GCr15 steel	Ti-Zr rod	Niu et al. (2023)

(Continued on the following page)

TABLE 4 (*Continued*) Tribological testing methods and testing parameters for titanium alloys.

Year	Test Method	Friction distance/stroke length	Sliding speed/reciprocating frequency	Load	Friction pairs	Substrate	Ref.
2023	Reciprocating wear	250 m	80 rpm	10 N		Titanium/Hydroxyapatite, Titanium/Silicon oxide dynamic compaction	Majzoobi et al. (2023)
2023	Ball-on disk	1 mm	25 Hz	50 N	AISI5200 steel	Ti-6Al-4V	Li et al. (2023)
2023	Reciprocating tribology	5 mm	1 Hz	2 N	Si_3N_4 ceramic	Ti-6Al-4V-xCu alloy laser powder bed fusion	Ju et al. (2023)
2023	Reciprocating sliding	5 mm	1 Hz	1 N	Zirconium-oxide (G10)	Ti-6Al-4V rod	Bian et al. (2023)
2022	Reciprocating sliding friction		2 Hz	15 N	Zirconium-oxide	TA2 pure titanium ROD	Zhang et al. (2022)
2022	Pin-on disk		200 r/min	100, 150 N	Pure TA2 annealed	GCr15 steel	Weng et al. (2022)
2022	Pin-on plate	20 mm	10 mm/s	0.1 N	Borosilicate glass	Ti6Al4V alloy (conventional manufacturing, additive manufacturing)	Ranusa et al. (2022)
2022	Nano-wear	20 μm		200 μN		Equal channel angular pressed Ti-28Nb-35.4Zr alloys	Munir et al. (2022)
2022	Ball-on-plate	3 mm	1 Hz	50 N	Al_2O_3 ceramic	Ti-6Al-4V–ZrO2	Madeira et al. (2022)
2022	Reciprocating friction				AISI5200 steel	Ti-6Al-4V	Li et al. (2022)
2022	Ball-on disk	200 m	10 mm/s	2, 10, 20 N	Al_2O_3 ceramic	Ti-6Al-7Nb alloy sintering	Hezil et al. (2022)
2022	Flat-on-flat reciprocating	100 mm		50 N	Bovine femoral bone	Ti-6Al-4V, NiTi alloys cast or selective laser melting	Costa et al. (2022)
2021	Vertical reciprocating wear test	5 mm	2 Hz	5 N	Si_3N_4 ceramic	Ti–6Al–4V alloy	Qin et al. (2021)
2021	Ball-on disk	6 mm	2 Hz	1 N	Ultra-high molecular weight polyethylene	TC4 alloy sheet	Liu et al. (2021b)
2021	Pin/ball-on-disk		50 mm/s	400 mN	Si_3N_4 ceramic	Pure titanium (Ti Grade 2) and commercial alloy Ti6Al4V (Ti Grade 5)	Budzyński et al. (2021)

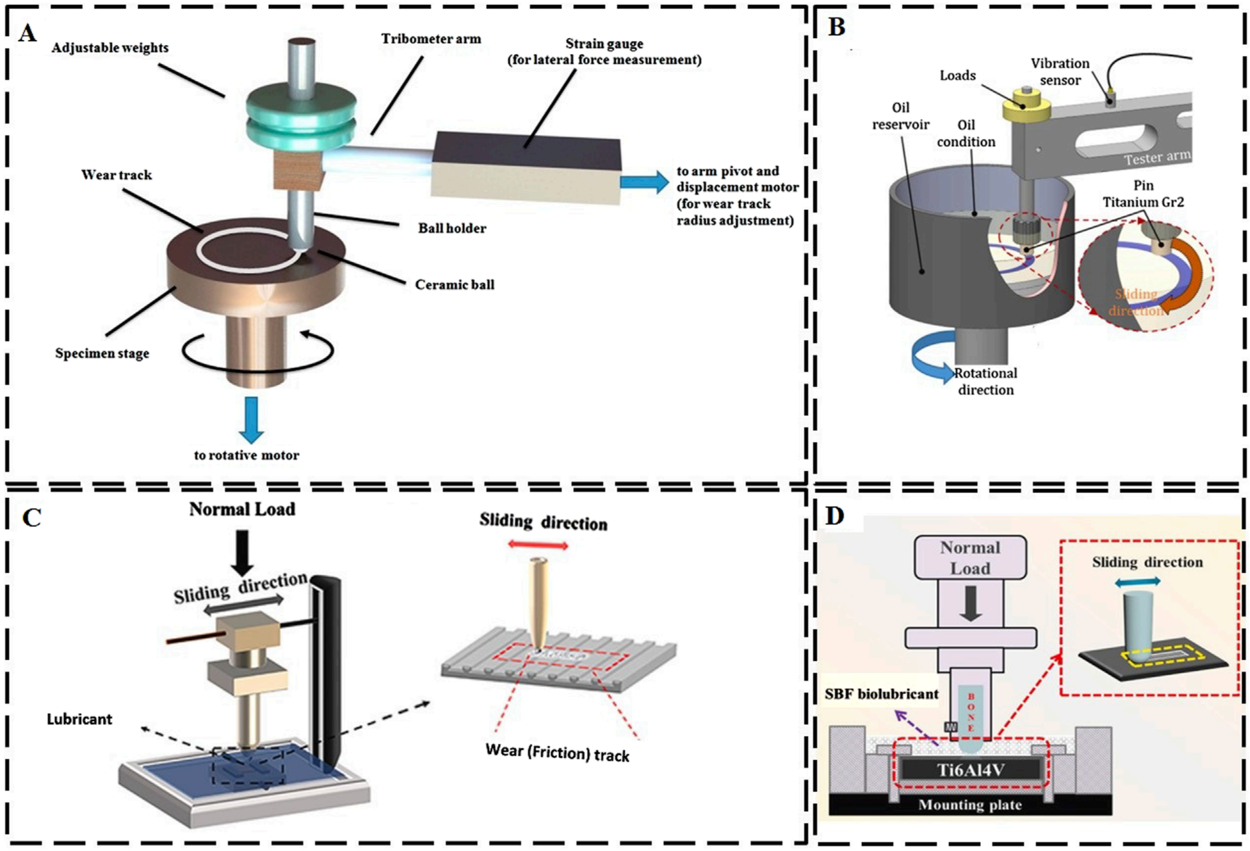

FIGURE 3
Tribological testing methods used for investigating tribological properties of Ti alloys in recent studies: **(A)** ball-on-disk, **(B)** pin-on-disk, **(C)** ball-on-plate, **(D)** pin-on-plate. **(A)** Reproduced with permission (Avcu, 2017a). Copyright 2017, Elsevier. **(B)** Reproduced under the terms of the CC-BY Creative Commons Attribution 4.0 International License (Şirin et al., 2023). Copyright 2023, The Authors, published by Elsevier. **(C)** Reproduced with permission (Zhang Y. et al., 2024). Copyright 2024, Elsevier. **(D)** Reproduced with permission (Wang et al., 2023b). Copyright 2023, Elsevier.

alloys, surface treatments and test conditions. For instance, (Wang et al., 2023a) investigated the wear scars of the pristine Ti6Al4V alloy, whose parametric properties are presented in Table 4, under oil lubricant conditions using the ball-on-disc method. The SEM image in Figure 6A was instrumental in determining the morphological structures of plough and adhesion. Similarly, (Li Y. et al., 2024) conducted a ball-on-plate test to investigate the wear properties of a chitosan-MXene-based hydrogel coating of the same alloy. Thus, it was observed that micro-crack formation occurred in the wear scars under conditions of lubrication with simulated body fluid (Figure 6B). Consequently, the machining phenomena of such as adhesion, micro-cutting, and micro-cracks occurring on the alloy surface can be demonstrated with clarity. Furthermore, the EDS (energy dispersive spectroscopy) characterization technique incorporated into the method enables the determination of elemental composition, elemental exchange and elemental contaminants between the wear site and the base alloy. For instance, (Wang et al., 2023a) demonstrated the formation of the adhesion wear mechanism by revealing the presence of Si, C and O elements resulting from the transfer of Si_3N_4 ceramic balls and residual lubricant in the EDS examination of the wear scars (Figure 6C).

The microstructure and type of materials are the primary determinants of their wear performance in a relative moving contact. Therefore, researchers incorporate this factor into comprehensive wear mechanism studies. The characterization of materials, the determination of crystal structures and the measurement of residual stresses can be achieved through the utilization of X-ray data obtained from the machined surface. For instance, (Zhang et al., 2022) examined the tribological properties of a titanium nitride (TiN) coating on TA2 pure titanium using a multi-arc ion plating (MAIP) method. Figure 7A illustrates the XPS (X-ray photoelectron spectroscopy) spectrum of Ti2p on the wear tracks formed under oil lubricant conditions by the reciprocating sliding friction test. Furthermore, the behaviour of the material grains and residual stresses can be demonstrated by utilizing the electron backscattered diffraction (EBSD) data obtained from the cross-sectional regions of the Ta alloys. For, instance, (Yu et al., 2024) conducted a study investigating the tribological behaviour of Ti6Al4V alloy produced by the selected laser melting method in the presence of SBF lubricant. Figure 7B illustrates the microstructure observed in the cross-section of the sample following the tribological test, as determined using the EBSD inverse pole figure (IPF) technique. Lastly, the determination of material crystal

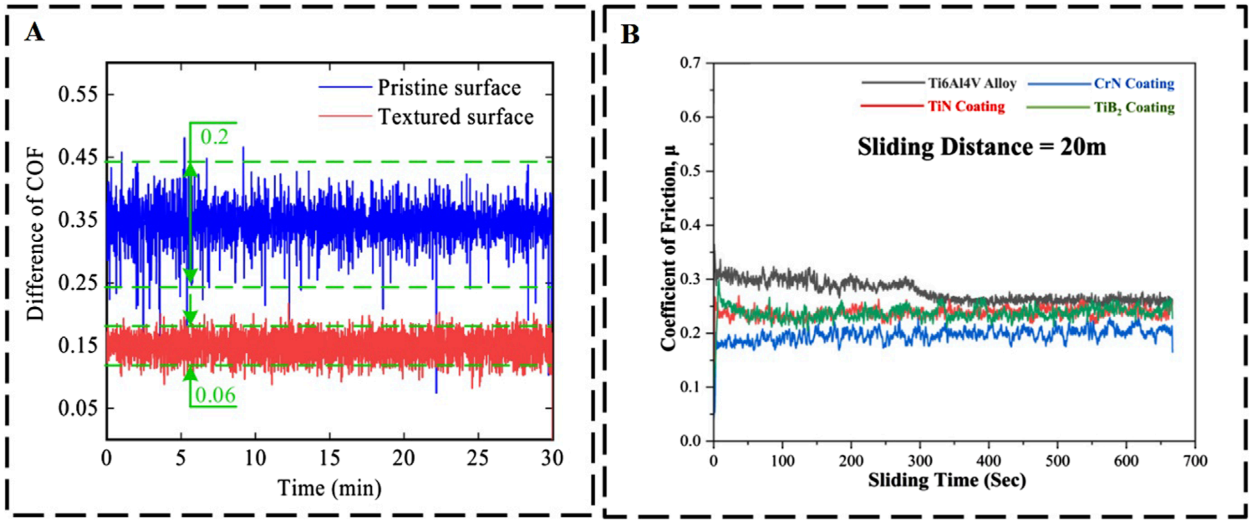

FIGURE 4
Force-time based friction graphs of Ti6Al4V alloy: **(A)** with laser texturing and simultaneous nitriding surface treatments, **(B)** with TiN, CrN and TiB2 coating by RF magnetron sputtering deposition. **(A)** Reproduced with permission (Wang et al., 2023a). Copyright 2023, Elsevier. **(B)** Reproduced with permission (Narayana and Saleem, 2024). Copyright 2024, Elsevier.

structures and distribution of can be achieved by transmission electron microscopy (TEM). Yang et al. (2024) conducted a TEM investigation of the microstructure of the tribolayer formed on the surface of the ATP-TiB/Ti composite material subjected to wear testing in a ball-on-disc tribometer (Figure 7C). Similarly, (Weng et al., 2022) conducted a study in which they tested TA2 pure titanium with a pin-on-disc under dry sliding conditions at room and cryogenic temperatures. Figure 7D illustrates the grain morphology and dislocation distribution as observed under bright field images in a TEM.

3.3 Shortcomings and future directions in tribological testing and characterization methods

Despite extensive research, tribological testing protocols applied to alloys and/or biomedical elements remain unclear. The majority of researchers have selected test methods and associated parameters based on the previous studies or their past experience. Furthermore, there are only few studies that include limb-specific tribological tests that take into account the different kinematic and biological structures of human limbs. The uncertainty in tribological test parameters in some literature is also noteworthy (refer to Table 4). All these factors point out to the need for the development of comprehensive protocols for tribological testing of titanium alloys.

To determine the wear mechanisms and corresponding cause-and-effect relationships, it is advisable to utilize a range of characterization techniques in tribological tests. A substantial body of research has shown that conventional load-cell-based wear testers remain crucial in the field (Maculotti et al., 2022). In the same manner, it is necessary to create suitable wear tests that accurately reflect the characteristics of limbs, kinematics, and biology. That being said, the use od advanced instruments have started in recent years (Davis et al., 2022; Liu et al., 2024c; Lypchanskyi et al., 2024; Qian et al., 2024; Srivastav et al., 2024) to study the various physical conditions that have emerged in titanium alloys through topographic, morphological, and microstructural examinations. The review showed that advanced characterization techniques can be used together with advanced detectors in scanning electron and transmission electron microscopes, such as EBSD and high-resolution transmission electron microscopy (HRTEM). Thus, it is recommended to incorporate advanced detectors and relevant data into future tribology studies on titanium.

Traditional studies on the tribological properties of titanium alloys lack certain elements that require further development and clarification. More specifically, the literature on tribological test parameters lacks studies that utilize statistical tools like design of experiments and analysis of variance (ANOVA) to assess the effects of these parameters. It is remarkable that these instruments have not been utilized in the study of friction, lubrication, and wear of biomedical titanium alloys despite their widespread application in the medical and health sectors. To determine and to optimize the tribological parameters and parameter levels of titanium alloys suitable for use in human limbs, future studies should focus on addressing the aforementioned shortcomings.

Finally, it is notable that machine learning methods such as artificial neural networks (Kumar et al., 2024), regression, and fuzzy logic, are yet to be employed in recent studies, where economic and efficiency considerations are of importance. There are almost no image processing studies employing deep learning for further characterization. The utilization of machine learning instruments for expeditious, cost-effective, and precise outcomes promises a significant potential for advancement. In the field of tribology, it

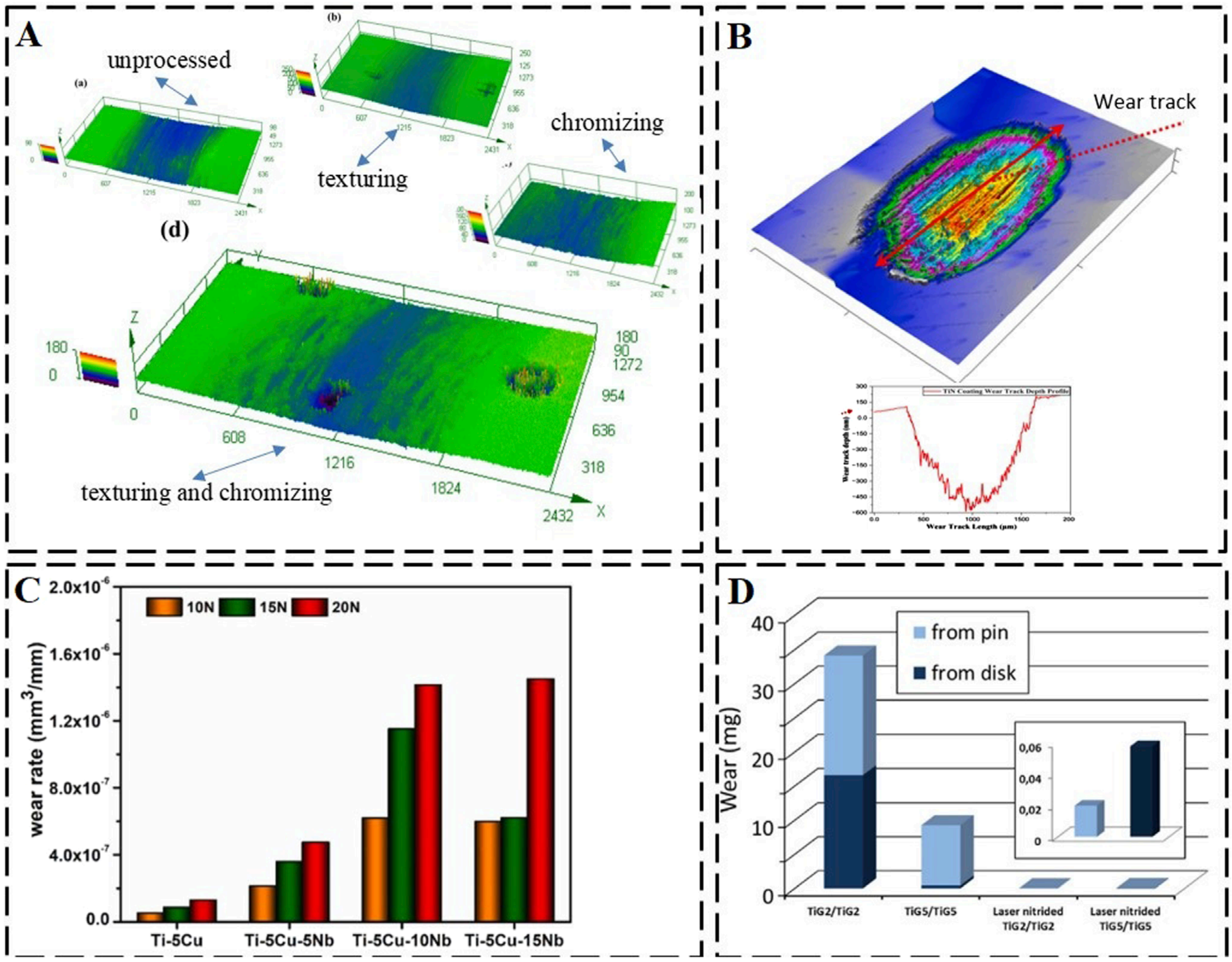

FIGURE 5
Wear: 3-D marks **(A)** laser confocal microscope, **(B)** optical profilometer analysis **(C)** wear rate, **(D)** wear amount. **(A)** Reproduced with permission (Lei et al., 2024). Copyright 2024, Elsevier. **(B)** Reproduced with permission (Narayana and Saleem, 2024). Copyright 2024, Elsevier. **(C)** Reproduced with permission (Pandey et al., 2023a). Copyright 2023, Elsevier. **(D)** Reproduced with permission (Chan et al., 2017). Copyright 2017, Elsevier.

is crucial to embrace a comprehensive approach that includes the design, implementation, and prediction stages.

4 Advances in developing biomedical coatings on titanium and alloys for tribological applications

Applying a coating to surfaces is an effective technique for enhancing the tribological characteristics of materials. These methods alter only the surface and subsurface characteristics of the material while leaving the properties of the bulk material unchanged. There are numerous coating methods that have been developed thus far, which can be categorized into two primary groups: modification methods and deposition methods. Plasma electrolytic oxidation (PEO), electron beam modification, anodization, chemical and physical vapor deposition (CVD and PVD), thermal spray, laser cladding, sol-gel, and nitriding are some of the topics that have been studied recently. Table 5 provides a concise overview of the coatings developed for biomedical titanium alloys in the field of tribological applications within the last 5 years.

4.1 Plasma electrolytic oxidation

Plasma electrolytic oxidation (PEO), also referred to as micro arc oxidation, is a technique employed to produce oxide-based coatings on valve metals' surfaces. The coating layer produced using this technique exhibits uniformity, strong adhesion to the substrate, substantial thickness, density, and hardness. The process is rapid, straightforward, environmentally friendly, and more efficient than alternative methods (Mao et al., 2024). Numerous review articles provide comprehensive information about every aspect of the process developed for various applications (Simchen et al., 2020; Aliofkhazraei et al., 2021).

PEO coatings can be applied to Ti alloys because they are hard and wear resistant. In a study by Zhong et al. (Zhong et al., 2023), PEO coatings on Ti30Zr5Al3V alloy were deposited, and

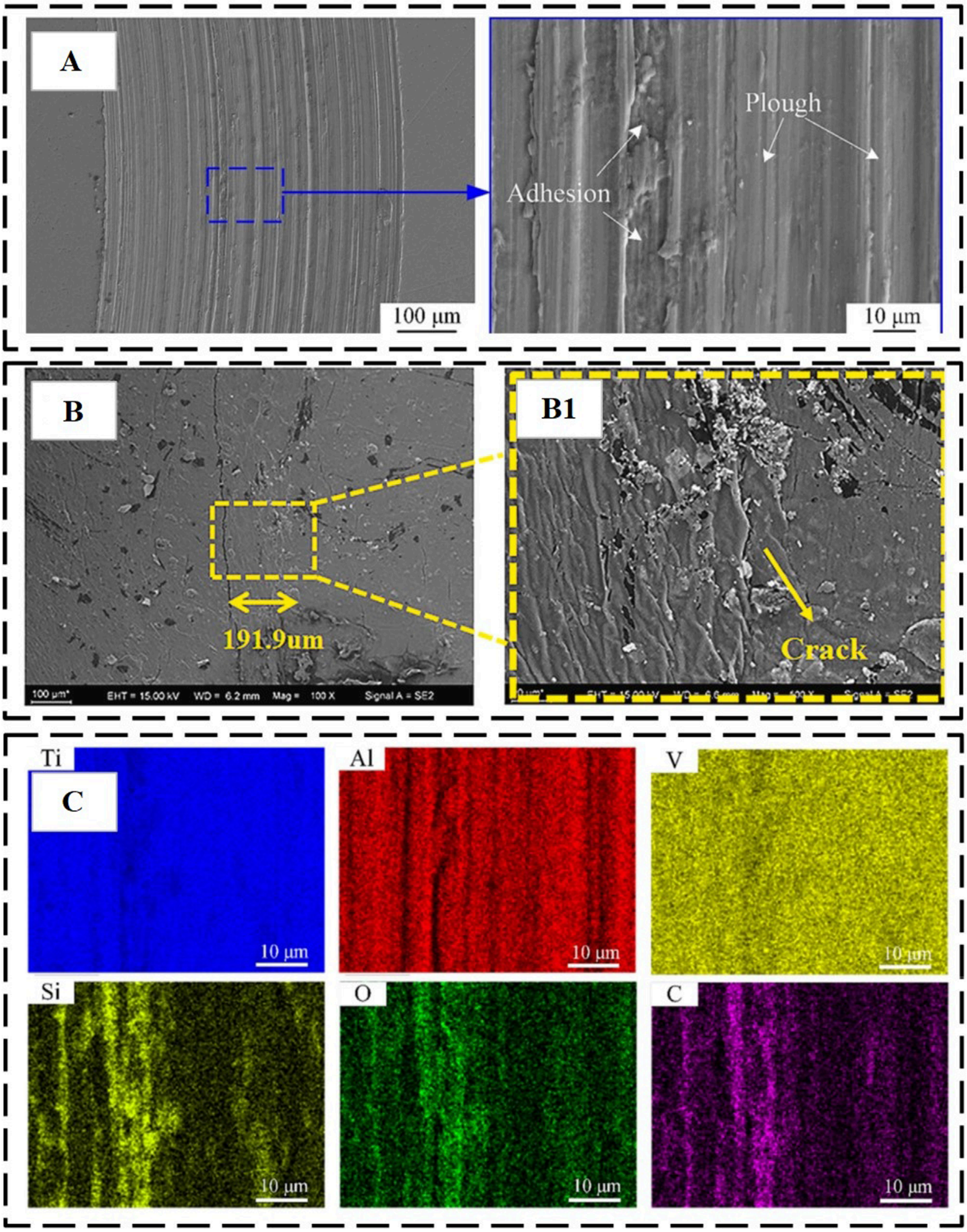

FIGURE 6
Determination of morphological structures in the wear scars by SEM: **(A)** adhesion and plough, **(B)** micro-cracks, **(C)** EDS elemental mapping. **(A)** and **(C)** Reproduced with permission (Wang et al., 2023a). Copyright 2023, Elsevier. **(B)** Reproduced with permission (Li Y. et al., 2024). Copyright 2024, Elsevier.

their tribological properties were examined. According to the results, process parameters had a significant effect on the friction coefficient and wear rate of the PEO layer (Zhong et al., 2023). Liu et al. (2024a) also produced PEO coatings on the surface of TC6 alloy and shown that the PEO coating improved the wear resistance of the TC6 alloy (Liu A. et al., 2024). Yang et al. (2023)

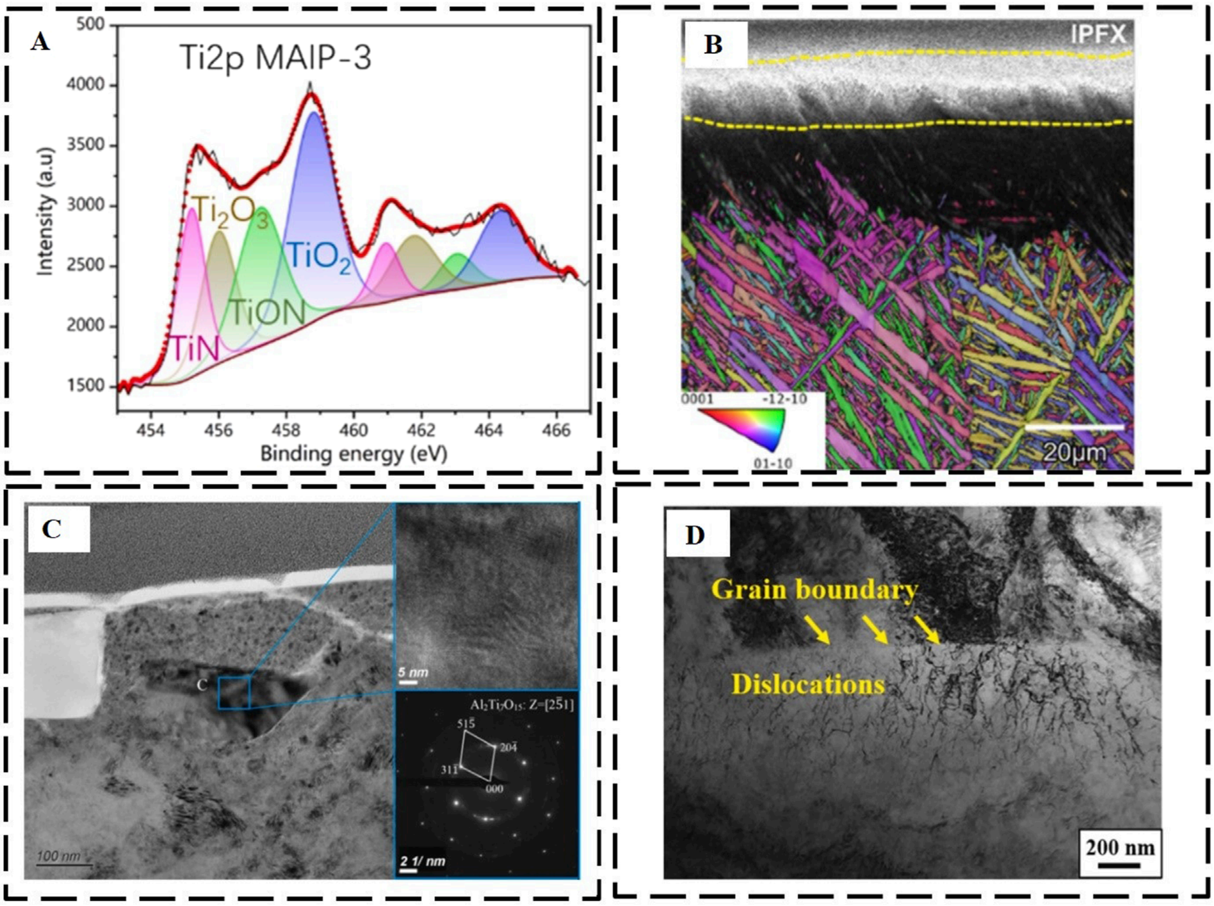

FIGURE 7
(A) XPS spectrum, **(B)** EBSD material grains, **(C)** TEM microstructure, **(D)** TEM dislocations and grain boundary. **(A)** Reproduced with permission (Zhang et al., 2022). Copyright 2022, Elsevier. **(B)** Reproduced with permission (Yu et al., 2024). Copyright 2024, Elsevier. **(C)** Reproduced with permission (Yang et al., 2024). Copyright 2024, Elsevier. **(D)** Reproduced with permission (Weng et al., 2022). Copyright 2022, Elsevier.

were reported similar results, where the PEO coating formed on the surface of the TC4 alloy wore 10.4% less than the TC4 alloy. PEO coatings inherently contain porosity, cracks, diffusion channels, etc. This structure that it possesses adversely affects the tribological properties of the coatings. Upon examining recent studies, it can be observed that efforts have been made to enhance the properties of PEO coatings by incorporating various additives such as Al_2O_3, MoS_2, TiC, and Y_2O_3 (Li and Wang, 2024; Liu A. et al., 2024; Shi et al., 2024; Tang et al., 2024).

4.2 Anodizing

Anodization is an electrochemical process employed to modify the surface of titanium and its alloys (Hang et al., 2020). In this method, a modification layer based on oxides is created, similar to the PEO method. Nevertheless, this approach involves a reduced applied voltage and an acidic electrolyte. The process offers several key advantages, including cost-effectiveness, suitability for complex geometries, uniform coating thickness, and straightforward process control. The properties of the oxide layer formed are significantly influenced by the applied voltage, time, and bath composition. The formation of TiO_2 is dependent on these variables and can result in either rutile or anatase forms. Research has indicated that the rutile form exhibits exceptional wear resistance and hardness (Yetim, 2010; Izmir and Ercan, 2018).

Şenaslan et al. (2023) investigated the wear characteristics of Ti45Nb alloy by subjecting it to various voltage levels. The results indicate that the form of TiO_2 and the thickness of the coating varied based on the different voltages used with an electrolyte containing H_2SO_4. The application of a voltage of 200 V resulted in the highest level of wear resistance. Asl et al. (2023) conducted a study where they utilized the anodization process on Cp-Ti, Ti6Al4V, and Ti45Nb alloys, applying the same process parameters. Based on the findings, the Ti45Nb alloy exhibited a more pronounced change in hardness compared to the other two alloys, with an increase of 94%. Ti45Nb alloy exhibited greater resistance to wear and higher hardness values, which were directly influenced by the amount of rutile present in its structure (Asl et al., 2023).

Upon reviewing the recent studies, it was observed that there is a scarcity of research on the tribological characteristics of anodized titanium and its alloys. The previous paragraph provides a summary of the existing literature on this topic. As stated earlier, TiO_2 exists in two distinct forms: rutile and anatase. Among these, rutile possesses greater hardness and is necessary in applications that demand high wear resistance. Therefore, research focused on enhancing

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TABLE 5 Applied coatings on biomedical Ti alloys in the field of tribological applications.

Year	Test Method	Friction distance/stroke length	Sliding speed/reciprocating frequency	Load	Friction pairs	Coating/Substrate	Ref.
2024	Reciprocating Tribology	10 min	1 Hz	3 N	GCr15	PEO/TC4	Tang et al. (2024)
2023	Ball-on-disc	100 min	300 rot min^{-1}	5 N	100Cr6	PEO/Grade 1	Muntean et al. (2023)
2021	Ball-on-plate	4 h	3 Hz	1 N	Y-Stabilized Zirconia	PEO/cpTi	Baldin et al. (2021)
2021	Ball-on-plate	4 h	1 Hz	1 N	Y-Stabilized Zirconia	PEO/Ti6Al4V	Santos et al. (2021)
2021	Ball-on-plate	300 s	100 mm/s	2 N	Cr-Coated	Electron beam modification/Ti6Al4V	Nikolova et al. (2021)
2023	Ball-on-disc	1000 m	25 mm/s	5 N	ZrO_2	Chemical Vapor Deposition/Ti6Al4V	Grenadyorov et al. (2023)
2021	Reciprocating Tribology	30 min	200 t/min	8 N	Si_3N_4	Plasma Nitriding + Chemical Vapor Deposition/Ti6Al4V	Zhang et al. (2020a)
2020	Ball-on-disc	1000 m	0.1 m/s	10 N	ZrO_2	Chemical Vapor Deposition/Ti6Al4V	Grabarczyk et al. (2020)
2020	Reciprocating Tribology	2000 cycles	1 Hz	5 N	Al_2O_3	Physical Vapor Deposition/Ti20Nb13Zr	Hussein et al. (2020)
2022	Pin-on-disc	1000 m	200 rpm	50 N	EN 31	Thermal Spray/Ti6Al4V	Thirumalvalavan et al. (2022)
2021	Pin-on-disc	30 min	400 rpm	5 N	Al_2O_3	Laser Cladding/Ti6Al4V	Liu et al. (2021a)
2021	Ball-on-disk	120 min	200 rpm	10 N	Si_3N_4	Laser Cladding/Ti6Al4V	Chen et al. (2021)
2024	Reciprocating tribology	30 min	2 Hz	10 N	Si_3N_4	Nitriding + Shot Peening/Ti6Al4V	Zhang et al. (2024c)

the plating bath and developing a rutile-based coating layer has demonstrated exceptional wear resistance.

4.3 Chemical vapor deposition

Chemical vapor deposition (CVD) refers to a group of techniques employed to produce usually hard coatings, typically a few microns thick, on the surfaces of metals and alloys. This technique involves the deposition of vaporized material onto a heated substrate material, either on its surface or within its interior. Coating properties can be influenced by factors such as the substrate material, process temperature, gas mixture, and gas flow pressure. The most commonly utilized types of chemical vapor deposition are traditional, minimal pressure chemical vapor deposition and plasma activated/assisted chemical vapor deposition (PACVD). Further information regarding the methodology can be located in other sources (Carlsson and Martin, 2010; Al-Asadi and Al-Tameemi, 2022).

Recent studies have shown that diamond-like-carbon (DLC) coatings are extensively studied for enhancing the tribological properties of titanium and its alloys. Ghio et al. (Ghio et al., 2023) conducted a study where they applied a DLC coating onto the surface of a Ti6Al4V alloy that was additively manufactured. They used the plasma-assisted CVD method for this process and then compared the properties of the DLC coating with those of PVD-AlCrN coatings. The DLC coating exhibited a lower coefficient of friction compared to the AlCrN coating (Ghio et al., 2023). Grabarczyk et al. (2020) investigated the impact of thermo-chemical treatments on the surface of Ti6Al4V alloy PVD and CVD coatings. According to the findings, carburization offers a low friction coefficient and wear rate (Grabarczyk et al., 2020). Zhang et al. (2020a) employed plasma-assisted CVD and plasma nitriding techniques to modify the surface of the Ti6Al4V alloy. The wear resistance was enhanced by this method, as indicated by the results (Zhang J. et al., 2020).

CVD is commonly employed to create thin film coatings that exhibit exceptional wear resistance and a low coefficient of friction. Due to the thin film characteristic of the coating layer, the parts used as biomaterials are susceptible to damages such as cracking and separation, which are dependent on the applied load. In light of this situation, researchers have conducted studies to enhance the coating characteristics of titanium and its alloys in CVD coating by implementing an additional technique, such as plasma nitriding. Nevertheless, there is a scarcity of research on the topic of biomedical titanium and its alloys, making it a crucial area in need of further investigation.

4.4 Physical vapor deposition

The formation of thin film coatings on the surface of materials is frequently achieved through physical vapor deposition (PVD). This method depends on the concept of transforming the target material into vapor through sputtering or evaporation, and then depositing it onto the surface of the material to be coated. Three of the most frequently employed PVD methods are sputter deposition, ion deposition, and vapor evaporation. The primary benefits of these coatings include high hardness, wear and corrosion resistance, high density, and good biocompatibility. Upon reviewing the recent literature, it is evident that a variety of coatings, including ZrN vr ta-C (Aslan et al., 2023), CrAlMoN (Bobzin et al., 2022), anodic alumina nanotubes (Sarraf et al., 2023), TiO2–SiO2 multilayer film (Çomaklı et al., 2023), and Ti3Au, are generally developed and applied to a variety of Ti alloys using PVD method (please see Table 5).

PVD, similar to CVD, is a technique used to produce thin film coatings that have excellent wear resistance and a low coefficient of friction, particularly on steel surfaces. Recent studies on PVD coating of titanium and its alloys have demonstrated the production of coatings with exceptional tribological performance. PVD coatings exhibit limited adhesion to the substrate material, and there is a potential for premature damage to occur as a result of the loading on the implants. To utilize PVD coatings in biomedical applications, it is necessary to enhance their properties while considering this circumstance.

4.5 Sol-gel coatings

Sol-gel coating technique allows for the obtaining of coatings on material surfaces that possess the desired biological properties and are resistant to wear and corrosion. The initial stage of the process involves the production of gel from the precursors through the use of appropriate reagents via the sol process. Subsequently, the gel is dehydrated and transformed into a solid state through the sintering procedure. It has been observed that this procedure is employed to enhance the tribological characteristics of titanium and its alloys. Al_2O_3/Gr/HAP (Shanmugapriya et al., 2021; Shanmugapriya et al., 2022), alumina/hydroxyapatite/graphene (Shanmugapriya et al., 2021), and graphene oxide (Li et al., 2020) coatings were obtained on the Ti6Al4V alloy surface using the sol-gel method.

Sol-gel is a coating technique that can effectively be used on titanium and its alloys. However, upon reviewing the studies conducted in recent years, it was observed that there were significant limitations in the research on the properties of these coatings, specifically in regards to corrosion, biocompatibility, and tribological properties. Hence, a thorough examination of the wear properties of these coatings is necessary for their application on implants.

4.6 Thermal spray coatings

Thermal spray coatings are a distinct category of coatings that are specifically applied to titanium and its alloys. This technique involves introducing feedstock, which can be in the form of powder, wire, rod, or suspension, into a spray torch. The feedstock is then sprayed onto the substrate material while it is in a molten or nearly molten state. Further information on thermal spray coatings can be found in other sources (Berger, 2015; Meghwal et al., 2020). Thermal spray methods are used to coat titanium and its alloys for biomedical applications. Upon careful examination of recent studies, hydroxyapatite coatings emerge as particularly notable (Singh G. et al., 2022; Hussain et al., 2023; Shankar et al., 2024). However, studies on the wear properties of these coatings are limited (Thirumalvalavan et al., 2022).

Thermal spray is extensively utilized in industrial applications to enhance wear resistance. Nevertheless, there is a scarcity of research investigating the tribological characteristics of biomedical titanium and its alloys. It is advantageous to incorporate research investigating the tribological characteristics of these coatings in the literature.

4.7 Laser cladding

Laser cladding has emerged as an extensively studied technique in recent years for enhancing the wear resistance of metals and alloys. This technique involves utilizing high-energy lasers to melt, solidify, and cool various materials such as powder, paste, or wire onto the surface of substrate materials. The resultant coating layers are of substantial thickness and exhibit exceptional adhesion properties to the substrate. Nevertheless, the expenses associated with investing in and maintaining this approach are substantial, and there is a risk of the substrate melting and experiencing segregation during the process. Comprehensive information regarding the method can be found in other sources (Wu Q. et al., 2024). The laser cladding method has been utilized in recent years to apply various coatings on the surface of titanium and its alloys, including but not limited to Ca/P (Liu B. et al., 2021), CaO-SiO2-MgO (Li et al., 2021), TiC/TiB (Chen et al., 2021), and TiNb (Zheng and Xu, 2023) enhancing their wear resistance.

Upon analyzing the recent studies, it is evident that laser cladding is a highly effective technique for enhancing the wear resistance of titanium and its alloys. Nevertheless, the cladding technique can result in chemical and microstructural irregularities within the coating layer. Additionally, there are challenges related to the inability to operate within tight tolerances. Addressing these issues has the potential to enhance the efficacy of the laser cladding technique for coating biomedical titanium and its alloys.

4.8 Nitriding

Nitriding of titanium and its alloys has been a subject that has been researched for a long time. Because the α-titanium phase can dissolve nitrogen at high rates and forms hard TiN and Ti_2N compounds. In this way, layers or regions with a hardness of up to 3000 HV are formed on the surfaces. The nitriding process can be carried out by methods with different mechanisms, the most common of which are gas, plasma, ion and laser nitriding. Details of these methods can be found elsewhere (Selamat et al., 2001; Zhecheva et al., 2005; Zhecheva et al., 2006; Jiang et al., 2022).

The nitriding process not only increases the hardness Ti alloys, but also causes a decrease in the friction coefficient and wear rate. Das et al. (2024) applied laser surface treatment to Ti6Al4V alloy in nitrogen atmosphere. A lower friction coefficient was reported as a result of the process (Das et al., 2024). The decrease in wear rate was also reported in studies by Shen and Wang (2023), Kaewnisai et al. (2023), and Xu et al. (2023).

Nitriding is a highly effective technique for applying a coating to titanium and its alloys, due to their desirable characteristics of high hardness, wear resistance, and low coefficient of friction. Recent studies have shown that this efficient technique is utilized on conventional titanium and its alloys, including cpTi and Ti6Al4V. This subject has the potential to significantly impact the field of nitriding and the tribological properties of new generation titanium and its alloys.

4.9 Coating interface

Surface coatings applied to biomedical titanium and titanium alloys could significantly improve the tribological performance of the materials. One of the main factors affecting the material performance is the behaviour of the interfacial surface between the titanium substrate material and the coating material. Therefore, efforts to achieve superior tribological performance by improving the interfacial properties have been the focus of research.

Efforts to improve the interface could be achieved by mechanical, chemical, and physical bonding mechanisms. For mechanical bonding, the roughening of the surface is essential. Methods such as sandblasting (Wang et al., 2024) and shot peening (Yıldıran et al., 2015; Avcu, 2017b) are preferred. In the context of chemical bonding, coating methods such as CVD (Liu et al., 2024b), PVD (Noori et al., 2023), and sol-gel (Murari and Chauhan, 2024) could be purposefully chosen in order to achieve the desired formation of covalent, ionic, and metallic bonds. Finally, physical bonding includes Van der Waals forces (Grubova et al., 2020) and hydrogen bonding (as seen in biomolecular coatings) (Tan et al., 2022). The connection types as well as the bonding mechanism of the interface could directly affect the tribological properties. For this reason, direct connection, use of interlayer (Ali et al., 2024), functional gradient coating (Singh J. et al., 2021), and laminated coating (Wu L. et al., 2024) have been investigated and applied for substrate material, coating material, and tribological expectations.

A variety of testing and characterisation methods are available for the purpose of evaluating the targeted tribological performance of interfaces. The phenomenon of adhesion strength (Błoniarz et al., 2024) has been observed in almost all studies. Tensile (Jang et al., 2024) and scratch (Singh et al., 2024) tests have been employed for this purpose. Additionally, other mechanical tests such as nanoindentation (Valentim Gelamo et al., 2024), abrasion (Khan et al., 2024), and fracture-crack resistance (Fernandes et al., 2024) may be conducted. Thermal cycling (Xu M. et al., 2024) tests are utilized to ascertain the behavior of the interface under thermal stresses. Finally, corrosion tests (Alontseva et al., 2024) are employed to determine chemical resistance. To determine the morphological and topographical effects of these tests, advanced characterization methods including scanning electron microscopy (SEM), transmission electron microscopy (TEM), X-ray photoelectron spectroscopy (XPS), and energy dispersive spectroscopy (EDS) are employed.

Modelling and simulation studies which consider together the coating, the substrate, and the interface provide an important opportunity for researchers to investigate areas such as preventive design and optimisation. To achieve this, researchers employ a range of techniques including the finite element method (Liu W. et al., 2024), molecular dynamics (Mirzayev et al., 2024) and Monte Carlo (dos Santos-Junior et al., 2024) simulations, density functional theory (Kaseem et al., 2024), and multiscale modelling (Liu et al., 2023). The finite element method is employed to examine a range of mechanical properties, including stress, deformation analysis, and crack propagation; whereas molecular dynamics simulations are utilized to investigate the mechanisms of interaction and bonding at the interface as well as the thermal behaviour associated with thermal expansion and heat conduction. Monte Carlo simulations are capable of replicating a multitude of performance characteristics including wear, surface roughness, diffusion, and corrosion. Density functional theory employs quantum mechanical principles to analyse the electronic structure and chemical bonding at the interface, and can also calculate surface energy and adhesion forces. Lastly, macro-level behaviours can be determined by applying micro-mechanical and nano-mechanical models with multi-scale modelling. A selection of software is available to improve the time and cost-effectiveness of these simulations and models. Overall, the advanced research topics of the interface presented above have notable research potential for academia-industry collaboration.

4.10 Shortcomings and future directions in coatings methods

A number of techniques including plasma electrolytic oxidation (PEO), anodization, chemical and physical vapor deposition, sol-gel, thermal spray, laser cladding, and nitriding can be used to enhance the durability and to reduce the friction of titanium and its alloys. PEO, laser cladding, and nitriding methods have particularly gained prominence in recent years. The presence of defects, such as porosity, cracks, and diffusion channels in the structure of PEO coatings has a detrimental impact on their wear resistance. The strategies for eradicating these defects have become a prominent concern in recent years. Furthermore, the laser cladding technique has garnered significant attention recently, necessitating further research on the implementation of novel coatings and the assurance of chemical and microstructural homogeneity. In addition, nitriding is a crucial technique for enhancing tribological properties through the application of a protective coating. Nevertheless, the studies conducted in recent years have solely concentrated on conventional titanium and its alloys, thereby necessitating an investigation into new generation alloys as well.

5 Advances in implementing mechanical surface treatment methods on biomedical Ti alloys for tribological applications

Most industrial application failures are related to material surface properties and microstructural features, such as fretting fatigue, fatigue fracture, fracture toughness (Armağan and Arıcı, 2021; Saxena et al., 2024; Wagih et al., 2024), wear (Avcu Y. Y. et al., 2023), cracks, scratches, and corrosion (Avcu E. et al., 2023). Nanocrystalline and ultrafine-grained materials obtained with mechanical surface treatment methods have enhanced friction, wear properties, and superior corrosion resistance due to improved surface and microstructural properties (e.g., hardness, strength, ultra-fine grained microstructures, etc.) (Li et al., 2017; Maurel et al., 2019). Tribological properties are enhanced by the formation of ultra-fine grains (UFG) at the surface with the implementation of mechanical surface treatment on Ti alloys. Severe plastic deformation (SPD) is often used to transform coarse-grained microstructure into ultrafine sized or nano grained microstructure (Subham et al., 2024) since nanocrystalline and ultrafine-grained materials possess numerous properties such as high hardness (Yildiran Avcu et al., 2020; Ganesh and Kumar, 2021; Avcu Y. Y. et al., 2023) and strength (Ganesh et al., 2014; Rajabi et al., 2019), excellent friction, wear properties (Li et al., 2017; Zhou et al., 2019; Singh S. et al., 2021; Das et al., 2024) and superior corrosion resistance (Subham et al., 2024) without any change in the chemical composition of the alloy. Grain refinement and high compressive residual stress are responsible for these improved properties (Alikhani Chamgordani et al., 2018). Over the past 2 decades, severe plastic deformation (SPD) methods for nanostructured material manufacturing have garnered attention.

Therefore, mechanical surface treatment methods like laser peening (LP) (Yin et al., 2018; Tong et al., 2019; Zhou et al., 2019; Gu et al., 2023; Praveenkumar et al., 2023; Das et al., 2024; Li J. et al., 2024), surface mechanical attrition treatment (SMAT) (Wen et al., 2011; Anand Kumar et al., 2013; Wen et al., 2014; Li et al., 2017; Alikhani Chamgordani et al., 2018; Maurel et al., 2019; Rajabi et al., 2019; Acharya et al., 2020; Singh S. et al., 2021), shot peening (SP) (Fridrici et al., 2001; Ganesh et al., 2012; Ganesh et al., 2014; Wang et al., 2018; Yang et al., 2018; Yildiran Avcu et al., 2020; DiCecco et al., 2021; Avcu Y. Y. et al., 2023; Vella et al., 2023; Subham et al., 2024), ultrasonic shot peening (USP) (Ji et al., 2023; Subham et al., 2024), and ultrasonic impact treatment (UIT) (Ji et al., 2023) have been used in order to improve their performance in the tribological applications. Mechanical surface treatment of Ti and Ti alloys improves surface and subsurface properties, particularly wear properties (Wen et al., 2014). Table 6 summarises some recent studies related to the use of mechanical surface treatment methods on improving tribological properties of biomedical Ti alloys.

5.1 Shot peening

The number of studies investigating the impact of shot peening (SP) on the tribological properties of engineering materials has recently increased (Ganesh et al., 2012; Wang et al., 2018; Yang et al., 2018; Yildiran Avcu et al., 2020; DiCecco et al., 2021; Moradi et al., 2022; Avcu Y. Y. et al., 2023; Ji et al., 2023; Vella et al., 2023; Subham et al., 2024). This is due to the fact that SP has the potential to enhance the tribological properties of Ti alloys, in addition to its well-known effect of enhancing the fatigue strength and service life of engineering materials. The repeated impact of high-velocity shots accelerated through a nozzle on the surfaces of materials via shot peening modifies their surface and subsurface properties (e.g., hardness (Yildiran Avcu et al., 2020; Avcu et al., 2021; Moradi et al., 2022; Vella et al., 2023), residual stress (Moradi et al., 2022), microstructural features (Yildiran Avcu et al., 2020; Moradi et al., 2022; Subham et al., 2024)), along with their tribological behaviour (Ganesh et al., 2014; Wang et al., 2018; Yang et al., 2018; Yildiran Avcu et al., 2020; Moradi et al., 2022; Vella et al., 2023). The tribological properties of

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TABLE 6 Recent studies employing mechanical surface treatment methods on biomedical Ti alloys for improving their tribological properties.

Material	Method	Tribology test	Parameters	Results	Ref.
Ti–6Al–4V Ti–6Al–7Nb	Shot peening	Pin-on-disc	Hardened steel disc, load 50N, linear sliding speed 1 m/s, distance 500 m	Shot peening can be considered as cost effective, time saving with superior advantages such as enhanced wear resistance and strength	Ganesh et al. (2014)
Ti-based amorphous alloy	Ultrasonic impact treatment (UIT)	Reciprocating wear test	Zirconia ceramic ball (Ø6 mm and 90 HRC) sliding stroke 5 mm, sliding speed 1000 mm min^{-1}, duration 60 min, load 2, 5, 7, 10, and 20 N	UIT led to noticeable reductions in both the coefficient of friction (COF) and the wear rate	Ji et al. (2023)
Ti–6Al–4V	Shot blasting	Reciprocating wear test	Steel ball (Ø6 mm and 60 HRC), frequency 5 Hz, stroke length 1 mm 2000 cycle, sliding speed 5 mm/s, distance 2000 mm	Considerable improvement in tribological properties and impart information on wear mechanisms attributing to an increase in wear resistance up to 76%	John et al. (2023)
Ti–6Al–4V	Shot peening	Pin-on-disc	-	Wear resistance of peened samples increased by 27% and 57%, compared to the raw specimen, respectively, due to the creation of severe plastic deformation, nanostructure, compressive residual stress, micro-strains and grain refinement on the surface.	Moradi et al. (2022)
Ti–6Al–4V	Ultrasonic shot peening	Pin-on-disc	Hank's solution, loads 5, 10 and 20 N, speed of the disc was 60 rpm, duration 4000 s	Resistance of Ti-6Al-4V alloy to tribocorrosion is significantly enhanced after USP	Subham et al. (2024)
Alpha titanium (Ti) with TiB	Shot peening	Ball-on-disc	AISI 52100 balls (Ø6 mm and 800 HV), loads from 1N to 17.5N, sliding speed 0.1 m/s	Shotpeened samples exhibited limited changes in wear behavior, remaining dominated by oxidation wear over the loading range	DiCecco et al. (2021)
Ti–6Al–4V	Shot peening	Ball-on-disc	Al_2O_3 ball (Ø6 mm), load 5N, distance 100 m, sliding speed 0.05 m^{-1}	Shot peening led to an increase in wear loss (maximum 25%) and a decrease in coefficient of friction (CoF) (maximum 12%) as similar wear mechanisms occurred at all samples	Yildiran Avcu et al. (2020)
Cp-Ti	Shot peening	Ball-on-disc	Al_2O_3 ball (Ø6 mm), load 15N, distance 300 m, sliding speed 94.24 mm/s	The coefficient of friction was similar for both shot-peened and unpeened samples, and changes in the sliding distance did not have a substantial effect	Avcu et al. (2023b)
Ti–6Al–4V	Shot peening	Reciprocating wear test	Al_2O_3 ball (Ø4.76 mm), load 1N, in three-electrode tribocorrosion cell	Peening was ineffective in enhancing the corrosion-wear resistance, as it does not protect the substrate from Type-I corrosion-wear	Vella et al. (2023)

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TABLE 6 (*Continued*) Recent studies employing mechanical surface treatment methods on biomedical Ti alloys for improving their tribological properties.

Material	Method	Tribology test	Parameters	Results	Ref.
Ti–6Al–4V	Shot peening	Ball-plate reciprocating bio-tribological tests	ZrO_2 balls (Ø5 mm,72–74HRC), load 10 N, velocity 100/min, duration 20 min, artificial saliva and 3 g L^{-1} sodium hyaluronate	Shot peening yielded a considerable improvement in the bio-tribological properties	Wang et al. (2018)
Ti–6Al–4V	Laser peening	Reciprocating wear test	WC ball (Ø10), load 10 N, frequency 10Hz, duration 30 min, stroke length 2 mm	Wear resistance improved	Das et al. (2024)
Ti–6Al–4V	Laser shock peening	Reciprocating wear test	Al2O3 ball (Ø10), load 5 N, frequency 2 Hz, duration 5 min, stroke length 12 mm	LSP treatment efficiently reduces the wear depth, wear width, and wear volume while enhancing the tribological properties of Ti-6Al-4 V alloy. A greater improvement in wear resistance is observed with an increase in laser intensity	Gu et al. (2023)
TC6	Laser peening	Reciprocating wear test	Si3N4 ball (Ø5), load 5 N, frequency 5 Hz, duration 5 min, sliding speed 0.1 m/s, stroke length 10 mm	Reinforced layer with higher hardness and more stable microstructure can be obtained through the new combined process with laser peening and ion implantation, which contributed to enhancing the strengthening effect of friction and wear resistance	Li et al. (2024a)
Ti–6Al–4V	Laser shock peening	Pin on disc	Counterpart EN31 steel (Ø165 mm × 8 mm, 62 HRC), loads 10, 20 and 30 N, sliding speed 2 m/s, distance 2000 m, temperature 28°C and 300°C	At ambient and elevated temperatures, the wear behaviour was improved for LPwC samples. At ambient temperature, LPwC samples show a reduced wear volume loss of 30, 24.75% and 17.08% than the unpeened samples at various loads (10, 20 and 30 N)	Praveenkumar et al. (2023)
TC11	Laser shock peening	Ball-on-disk	Al_2O_3 ball (Ø10 mm), loads 10, 15, 20 and 25 N, sliding speed 100 r/min, duration 20 min, temperature 25, 400, 500°C and 600°C	The wear conditions have significant effect on the wear rate and the lowest wear rate is obtained for the LSPed specimen under the applied load of 15 N at 500°C	Tong et al. (2019)
TC17	Laser shock peening	Impact-sliding fretting wear test	Silicon nitride ceramic ball (Ø9.52 mm), fretting cycles (500, 1000, 1500, 2000, 3000), impact force 10 N)	Wear resistance of both treated samples improved compared with the untreated alloy	Yin et al. (2018)
Ti–6Al–4V	Laser peening	Ball-on-disk	GCr15 ball (Ø8 mm, 750 HV, Ra <0.1 μm), sliding speed 120 r.min^{-1}, sliding radius 3 mm, duration 30 min, load 5N in Hank's solution at room temperature	The average COF and wear mass loss were significantly reduced to 50% and 29.2%, respectively, as a result of the increasing laser energy and impact times. LP treatment could effectively improve the friction and wear properties of the medical Ti6Al4V alloy	Zhou et al. (2019)
Ti-NbTa-O alloy	SMAT	Ball-on-plate fretting wear	ZrO2 balls (Ø6 mm), frequency 10 Hz, displacement 200 μm, 50.000 fretting cycles, normal load 5N, 20% fetal bovine serum (FBS) solution, temperature 37.4°C	Wear resistance was enhanced after SMAT, with 32% decrease in wear volume loss and 21% decrease in friction coefficient resulted due to improved ductility on the surface	Acharya et al. (2020)

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TABLE 6 (*Continued*) Recent studies employing mechanical surface treatment methods on biomedical Ti alloys for improving their tribological properties.

Material	Method	Tribology test	Parameters	Results	Ref.
Cp-Ti	SMAT	Pin-on-disk	AISI52100 steel pin (Ø3 mm and 848 HV), linear distance of 275 m load 3N duration 20 min	Increase in hardness was due to plastic deformation and work-hardening. SMAT led to improvement of wear properties in CP-Ti so that its friction coefficient decreased by 66%. On the other hand, wear rate of CP-Ti samples decreased by about 60%	Alikhani Chamgordani et al. (2018)
Ti–6Al–4V	SMAT	Fretting wear	Two counterbody materials (alumina and steel (Ø10 mm)), constant frequency 5 Hz displacement 50 mm 25.000 fretting cycles, normal loads (1.96, 4.9, 9.8, 14.7 and 19.6 N)	Due to high hardness, low tangential force coefficient and more TiO_2 layer, fretting wear resistance of SMAT treated samples was higher than that of the untreated samples	Anand Kumar et al. (2013)
Ti–6Al–4V	SMAT	Ball-on-disk	GCr15 balls (Ø 6 mm), sliding speed 560 $r.min^{-1}$, sliding radius 2 mm and testing time 15 min	The friction coefficient of the SMAT samples are obviously lower than that of the Ti– 6Al–4V substrate, indicating that the friction behavior of substrate is improved after SMAT.	Li et al. (2017)
Cp-Ti	SMAT	Pin-on-disk	AISI 52100 steel ball (Ø 6 mm, 840 HV), speed 11 mm/s sliding distance 200 m load 2 N	Nanostructured surfaces obtained by SMAT have led to high hardness values but, in a rather counter intuitive manner, to a detrimental wear behavior	Maurel et al. (2019)
Cp-Ti	SMAT	Pin-on-disk	AISI52100 steel pin (Ø 7 mm, 848 HV), sliding velocities 0.052 and 0.1046 $m\ s^{-1}$ loads 1, 2 and 5 N	Despite the increase in hardness by 2.6 times after SMAT, wear properties of treated samples were diminished	Rajabi et al. (2019)
Ti-6Al-4V	SMAT	Ball-on-disc	Speed 250 rpm, radius of wear track 7.5 mm, sliding distance 500 m load 1 N	Wear resistance of the SMATed surface improved with a ~23% decrease in wear rate, which may be credited to the formation of nanograins over the whole surface or to the creation of stable TiO2 film over the surface	Singh et al. (2021b)
Cp-Ti	SMAT	Ball-on-disc	Linear speed 20 mm/s, radius of wear track 2.5 mm sliding distances 30 m loads 1–5 N	The friction coefficient and wear volume decrease after SMAT treatment, which can be attributed to the refined grain size and higher hardness	Wen et al. (2011)

the material are also significantly influenced by the surface work-hardening and changes in surface roughness that are caused by shot-peening. (Yildiran Avcu et al., 2020; Avcu Y. Y. et al., 2023; Subham et al., 2024). SP offers several advantages compared to SPD methods, such as minimal equipment requirements, the ability to adjust surface and subsurface properties through changes in process parameters, low energy consumption, short processing time, the ability to apply complex shapes to workpieces, and high production efficiency (Avcu et al., 2021).

There are reports available that discuss the tribological behavior of biomedical titanium alloys. The wear resistance of SPed Ti-6Al-4V was enhanced by 57% as a result of the formation of severe plastic deformation, nanostructure, compressive residual stress, micro-strains, and grain refinement on the surface (Moradi et al., 2022). The enhancement of surface hardness in the SPed Ti-6Al-4V has led to an improvement in the specimen's wear resistance. Oxidative wear has been observed in specimens tested at lower sliding speeds, while delaminative wear has occurred at higher sliding velocities. (Ganesh et al., 2012). Several studies have shown that SP had minimal impact on the coefficient of friction (COF) and wear rates. The COF and wear rates were found to be similar when using a steel ball (DiCecco et al., 2021) and an alumina (Avcu Y. Y. et al., 2023) counterface, and the observations of debris were also comparable (DiCecco et al., 2021; Avcu Y. Y. et al., 2023). The study confirms that the influence of SP on the wear behavior of Ti–6Al–4V under fretting conditions is negligible. This is evident from the observation that experiments conducted with polished or shot peened specimens, with different displacement amplitudes, result in the same cumulated dissipated energy and wear measurements for both types of specimens (Fridrici et al., 2001). The main distinction observed between the wear testing results of the SPed and untreated samples was that wear in the SPed samples was primarily caused by oxidation (DiCecco et al., 2021).

5.2 Laser peening

Recently, enhancing of the wear resistance of metal alloys via laser surface modification methods, such as laser peening (LP) (Zhou et al., 2019) or laser shock peening (LSP) (Tong et al., 2019), and laser surface treatment (LST) (Das et al., 2024), have attracted great interest. Laser peening (LP) has the ability to create a plasma with high pressure, which can apply compressive residual stress to the surface (Yin et al., 2018; Praveenkumar et al., 2023), increase the surface micro-hardness (Zhou et al., 2019; Gu et al., 2023; Das et al., 2024; Li J. et al., 2024), and refine the grain of Ti alloys (Yin et al., 2018; Praveenkumar et al., 2023) to improve fatigue, wear (Das et al., 2024), tensile, and corrosion properties (Tong et al., 2019; Zhou et al., 2019).

LST technique offers several advantages compared to other surface treatment methods. These advantages include faster processing speed, minimal heat affected zone and structural deformation, higher precision, and environmental friendliness (Das et al., 2024). In the past, the technique has been effectively used to alter the microstructure and/or composition of titanium and its alloys in order to enhance their properties for biomedical purposes (Das et al., 2024). Laser surface treatments are sophisticated techniques used to create micro-scale structures on the surface of medical Ti6Al4V alloy. These structures are designed to improve the alloy's ability to resist wear and tribo-corrosion under various process parameters (Yin et al., 2018; Zhou et al., 2019; Das et al., 2024).

The surface micro-hardness of the LPed Ti-6Al-4V was augmented by a substantial 25.7%, and the hardened layer extended to a depth exceeding 0.3 mm. The mean coefficient of friction (COF) and the amount of wear mass loss were both significantly decreased to 50% and 29.2%, respectively, due to the higher laser energy and increased number of impacts (Zhou et al., 2019). At higher temperatures, the wear performance of LPed samples was enhanced, with a reduction in wear volume loss of 30.3%, 19.58%, and 13.43% compared to the unpeened samples under different loads (10, 20, and 30 N) (Praveenkumar et al., 2023). The application of LSP treatment effectively decreases the depth, width, and volume of wear, while simultaneously improving the tribological characteristics of the Ti-6Al-4V alloy (Gu et al., 2023). An enhanced enhancement in wear resistance is observed as laser intensity increases (wear volume decreases by 27.2%) (Gu et al., 2023). The wear process of Ti-6Al-4V alloy primarily involves three mechanisms: abrasive wear, fatigue wear, and oxidation wear (Gu et al., 2023). The enhanced tribological characteristics of the LPed specimen can be attributed to work hardening, compressive residual stress, and refined grain. These factors effectively delay the initiation and propagation of cracks during the wear process (Tong et al., 2019).

5.3 Surface mechanical attrition treatment (SMAT)

Surface mechanical attrition treatment (SMAT) is a well-known method in the scientific community for producing a nanostructured layer on metal surfaces. It is one of several severe plastic deformation (SPD) methods that have gained significant attention (Singh S. et al., 2021). During the process of SMAT, spherical balls with a polished surface are placed inside a chamber that reflects light. The chamber is then vibrated using a device that generates vibrations. The samples that are being treated are attached to the top side of the chamber. Resonating the balls results in a rapid and intense bombardment of the sample surface by a multitude of flying balls. (Wen et al., 2011). Consequently, successive plastic deformations occur through repeated impacts from various directions, resulting in significant plastic deformation and the reduction of grain size to nano-scale dimensions (Rajabi et al., 2019). SMAT results in a nanostructured surface, enhanced mechanical properties (Acharya et al., 2020), high hardness (Anand Kumar et al., 2013; Alikhani Chamgordani et al., 2018; Acharya et al., 2020), good wear resistance while keeping the overall composition and/or phases unchanged and without changing chemical compositions (Li et al., 2017) and any contamination (Anand Kumar et al., 2013).

The improvement in wear resistance is due to the presence of a nanostructured surface that has a higher level of hardness. This increased hardness is primarily a result of grain refinement and strain hardening, which is achieved by mechanically applying a high amount of strain energy. Research on the tribological properties of nano/ultrafine grained surface materials has been restricted due to the challenges in creating samples that are suitable for friction and wear testing (Anand Kumar et al., 2013). For instance, certain studies have shown that the wear rates of samples treated with surface mechanical attrition treatment (SMAT) were greater than those of untreated samples. Put simply, there was a difference between the increase in hardness and the decrease in wear rate. Due to its inherent low toughness, the hardening treatment of titanium resulted in a degradation of its toughness. As a result, the samples eventually cracked and fractured during the wear process, indicating a reduction in wear resistance (Rajabi et al., 2019). However, the wear resistance was improved after SMAT, as evidenced by a 32% reduction in wear volume loss and a 21% decrease in friction coefficient. These improvements can be attributed to the enhanced ductility on the surface (Acharya et al., 2020). The wear resistance of CP-Ti was significantly enhanced. The friction coefficient of CP-Ti was decreased through the use of SMAT. As the treatment duration increased, the friction coefficient decreased even more, reaching a reduction of 66% by the end of the process. The increase in SMAT duration resulted in the elongation of the initial low friction coefficient stability, which can be attributed to the increase in the depth of the deformation layer (Alikhani Chamgordani et al., 2018). The samples treated with SMAT demonstrated reduced wear volume and specific wear rate in comparison to the untreated samples. When comparing samples fretted against alumina balls to samples fretted against steel balls at lower normal loads, the former showed higher wear volume and specific wear rate. The wear mechanism observed in this case is caused by three-body abrasion, which is induced by the generation of abrasive hard wear debris resulting from a tribochemical reaction between the Ti–6Al–4V sample and the alumina ball (Anand Kumar et al., 2013).

5.4 Shortcomings and future directions in mechanical surface treatments

Currently, shot peening, laser peening, and surface mechanical attrition are the most commonly employed mechanical surface treatment techniques for enhancing the tribological performance of biomedical Ti alloys. To achieve the optimal tribological properties for tailored applications, further research is required on the processing parameters of these methods such as shot size, pressure, laser power, contact pressure, cover rate, etc. The research area of hybrid and innovative water jet shot peening (Hou et al., 2022; Chakkravarthy et al., 2023; Wang G. et al., 2023; Wang Z. et al., 2023; Lu et al., 2024) which combines the techniques of shot peening (Yıldıran et al., 2015; Yildiran Avcu et al., 2020; Avcu et al., 2021) and abrasive water jet machining (Armağan and Arıcı, 2017; Armağan, 2021; Armağan and Arıcı, 2024b; Armağan and Arıcı, 2024a), is gaining increasing interest. Finite element modelling has already been utilized (Daoud et al., 2021; Zhou et al., 2022; Huang et al., 2023) to project the plastic strain and residual stress based on mechanical surface treatment parameters, demonstrating a good potential in the field. Nevertheless, there is a lack of research on modeling studies aimed at predicting tribological properties such as coefficient of friction and wear rate. Therefore, research in this area is anticipated to grow due to the time-consuming and expensive nature of investigating the relationship between processing parameters and tribological performance. Using these methods before the coating process has shown great potential (Cao et al., 2020; Dong et al., 2022; Xiao et al., 2022) in enhancing the adhesion, mechanical, and tribological properties of the coatings. Consequently, there is a projected increase in research focused on combining mechanical surface treatment techniques with coating technologies within the field.

6 Advances in developing biomedical grade Ti matrix composites for tribological applications

Titanium matrix composites (TMCs) consist of a titanium matrix and a reinforcing element, which can be a metal, ceramic, or organic compound (Somasundaram Prasadh et al., 2021). When considering composite material structures, it is advantageous to utilize the combined impact of the exceptional characteristics of both the matrix and reinforcing elements. Therefore, conducting research in the domain of composite design and production has the potential to improve the performance of implants. Moreover, the healthcare sector can verify the economic feasibility and reliability of implants to the degree that they are supported by scientific evidence. Titanium matrix composites have the potential to greatly enhance lifetime and reliability through their tribological behavior (Sousa et al., 2022). This chapter provides a review of the research conducted in the past 5 years on the tribological properties of titanium matrix composites, focusing on their design, manufacturing, testing, and performance characteristics.

6.1 Processing and composition of Ti matrix composites

The design and manufacturing conditions of titanium matrix composites exert a direct influence on their tribological behaviour. The matrix, reinforcement and operating conditions of composites attribute these behaviors to three main factors. The initial main factor concerns such as the type, shape, size, volume fraction and distribution of the reinforcing elements within the matrix phase. Phase structures affecting the hardness of titanium and operating conditions such as load, cycle, frequency, sliding distance and usage time constitute the other two main factors (Lal and Dey, 2024b). The choice of reinforcing elements for titanium matrix composites is influenced by various design objectives, such as ensuring biocompatibility (Kumar et al., 2021; Somasundaram Prasadh et al., 2021; Afrouzian and Bandyopadhyay, 2023), improved wear and corrosion resistance, and high hardness (Sousa et al., 2021a; Sousa et al., 2021b; Sousa et al., 2022). It is preferable for the reinforcing elements to exhibit isotropy and possess a high level of hardness (Gonçalves et al., 2023). In recent years, there has been a preference for the use of reinforcement materials such as TiC (Lal and Dey, 2024a; b), Al_2O_3 (Afrouzian and Bandyopadhyay, 2023; Sousa et al., 2023), TiB (Singh N. et al., 2022), hydroxyapatite (Somasundaram Prasadh et al., 2021; Afrouzian and Bandyopadhyay, 2023), Si_3N_4 (Afrouzian and Bandyopadhyay, 2023), NbC (Gonçalves et al., 2023), ZrO_2, nitinol and Mg (Somasundaram Prasadh et al., 2021) in research.

The previously mentioned design outcomes, specifically biocompatibility, enhanced wear and corrosion resistance, are

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TABLE 7 Conditions for tribological tests on titanium matrix composites.

Test Method	Stroke length /cycle	Sliding speed/reciprocating frequency	Load	Friction pairs	Lubricant or Tribocorrosion	Matrix material	Reinforcement material	Processing Method	Year	Reference
Ball-on-disc	150 µm / 20000 cycles	1 Hz	20 N	SS316L ball		Ti6Al4V	TiC	Spark plasma sintering	2024	Lal and Dey (2024a)
Ball-on-disc	20000, 50000, 80000 cycles	1, 5.5, 10 Hz	50, 100, 150 N		Dry	Ti6Al4V	TiC	Spark plasma sintering	2024	Lal and Dey (2024b)
Ball-on-plate	5 mm / 1800-3600 s	1, 2 Hz	1, 2 N	Alumina ball	Tribocorrosion	Ti grade 2	Al2O3	Sintering	2023	Sousa et al. (2023)
Ball-on-plate	3 mm /3600 s	1 Hz	0.5, 10 N	Alumina ball	Tribocorrosion	Ti grade 2	TiB-TiC, B4C	Sintering	2024	Sousa et al. (2024)
Ball-on-plate	2000 mm / 2000 cycles	5 Hz/4 mm/s	1, 2, 3 N	Steel ball	Simulated body fluid	Ti6Al7Nb	TiB	Selective laser melting	2022	Singh et al. (2022b)
Ball-on-plate	10 mm/ 1000 mm	1200 mm/min	10 N	ZrO2	Bio-tribocorrosion	Ti6Al4V	Al2O3, Si3N4, HA	Laser based directed energy deposition	2023	Afrouzian and Bandyopadhyay (2023)
Pin-on-disc	2 mm / 30 min	0.32 Hz	1 N	Alumina	Tribocorrosion	cp Ti, β type Ti–40Nb	NbC	Arc-melting	2023	Gonçalves et al. (2023)
Ball-on-plate	10 mm / 1000 m	1200 mm/min	7 N	WC, HCS, ZrO2	Deionise water ,Dulbecco's Modified Eagle Medium	Ti6Al4V	HA	Laser based directed energy deposition	2021	Avila et al. (2021)
Pin-on-disc	300 m	0.1 m/s	10 N	Hardened steel pin		Cu-Ti	TiC	Sintering assisted by abnormal glow discharge	2020	Bohórquez et al. (2020)
Ball-on-plate	3 mm / 3600 s	1 Hz	0.5, 10 N	AL2O3	Tribocorrosion	Ti grade 2	TiB-TiC	Hot-pressing	2022	Sousa et al. (2022)
Ball-on-plate	3 mm / 1800 s	1 Hz	1 N	AL2O3	Tribocorrosion	Ti grade 2	Al2O3	Hot-pressing	2021	Sousa et al. (2021b)
Ball-on-plate	3 mm / 1800 s	1 Hz	1 N	Alumina ball	Tribocorrosion	cp Ti	NbC	Hot-pressing	2022	Gonçalves et al. (2022)
Ball-on-plate	3 mm / 1800 s	1 Hz	1 N	Alumina ball	Tribocorrosion	Ti grade 2	B4C	Conventional powder	2021	Sousa et al. (2021a)
Ball-on-plate	5 mm / 1800 s	1 Hz	1 N	Alumina ball	Tribocorrosion	Ti-25Nb-5Fe	TiN2	Sintering	2021	Çaha et al. (2021)

also applicable to biomedical titanium matrices. The alloy type and production conditions of the matrix have a direct impact on the phase structure, and it is therefore essential that they are compatible with the reinforcing element. In recent years, especially Ti grade 2 (Sousa et al., 2021a; Sousa et al., 2022; Sousa et al., 2023; Sousa et al., 2024), Ti6Al4V (Avila et al., 2021; Afrouzian and Bandyopadhyay, 2023; Lal and Dey, 2024a; b) and Ti-Nb (Somasundaram Prasadh et al., 2021; Gonçalves et al., 2022; Singh N. et al., 2022; Gonçalves et al., 2023) alloys are preferred as matrix materials. In addition, the principles of laser deposition (Singh N. et al., 2022; Afrouzian and Bandyopadhyay, 2023), sintering (Çaha et al., 2021; Sousa et al., 2023) and hot pressing (Sousa et al., 2021b; Gonçalves et al., 2022) are becoming more favored in the manufacture of Ti matrix composites.

6.2 Tribological testing of Ti matrix composites

Conventional tests, such as ball-on-disc tests (Lal and Dey, 2024a; b), along with advanced tribocorrosion tests (Sousa et al., 2021a; Sousa et al., 2021b; Gonçalves et al., 2022), accurately simulate the operating conditions of titanium matrix composites and comprehensively analyze the tribological behavior by considering all relevant factors. Table 7 presents a summary of the tribological tests applied to titanium matrix composites over the past 5 years. The studies showed that the ball-on-plate test method was used more often. Moreover, when the stroke length is 3 and 5 mm, the reciprocating frequency is 1 Hz, the load is 1 N, and the friction pair is alumina, these conditions are commonly preferred. An noteworthy trend in recent years has been the widespread increase in tribocorrosion tests. Consequently, tribological testing in corrosive environments, such as body fluids, is a more accurate representation of the performance of biomedical titanium matrix composites in humans than testing in dry or lubricating environments.

Sousa et al. (2021a) examined the design and production conditions of Ti grade 2 matrix and B_4C reinforced composites by conventional sintering and hot-pressing techniques. The study has shown that the interaction between the matrix and reinforcement differs depending on the production conditions. Conventional sintering resulted in the formation of significantly thicker reaction zones, smaller B_4C particles and a greater degree of porosity. Such factors can directly impact the performance characteristics of the material, including mechanical, tribological and biocompatibility properties.

Sousa et al. (2021a); Sousa et al. (2021b); Sousa et al. (2023) studied the effects of different manufacturing and reinforcement elements with the Ti grade 2 matrix in tribocorrosion tests that offer a number of benefits. The tribological formation differences of Ti grade 2, Ti-Al_2O_3 and Ti-B_4C composites by conventional sintering (PM) and hot-pressing (HP), according to similar test conditions detailed in Table 1. A visual inspection reveals that the greatest wear is observed in Ti grade 2, while the least wear is observed in the composite with Al_2O_3 reinforcement. It can be further observed that samples produced by hot-pressing exhibit reduced wear. It can be posited that the observed changes in tribological performance are a consequence of the microstructural alterations to the production methods. Finally, scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS) images of the test element, alumina ball, corroborate the aforementioned observations.

6.3 Shortcomings and future directions in titanium matrix composites

The previously explained limitations of titanium matrix biomedical composites also highlight several underexplored areas in the field of tribological studies. There are multiple types of titanium alloys, several reinforcement elements, and various manufacturing methods used. The predominant focus of research on tribological improvements in composites has been on the characteristics of the reinforcing component such as its type, amount, and distribution. However, only a few studies have examined the variations in production methodology. Furthermore, there are still notable shortcomings in the domain of advanced process causation, particularly in areas such as parametric optimization and machine learning. The choice of Ti grade 2 and Ti6Al4V alloy as matrix materials represents a departure from previous conventional practices in the manufacturing of composite materials. Researchers are advised to embrace a comprehensive approach when it comes to the design and production processes of composites. This will enhance the ability to precisely convey cause-and-effect relationships. In addition, the inclusion of statistical gains, such as variance analysis on all design, process, and performance outcomes, will guarantee the establishment of consistent, quantifiable, and similar conditions. The utilization of parametric optimization and machine learning is highly recommended since processing of Ti matrix composites is a challenging and costly task.

7 Conclusion

Titanium (Ti) alloys are extensively utilized in biomedical applications due to their exceptional mechanical, physical, and surface characteristics. However, enhancing their tribological properties is crucial for expanding their range and performance of biomedical applications. The present review analyzes the latest advancements in improving the tribological characteristics of titanium alloys and titanium matrix composites for biomedical applications. The advances in enhancing the performance of Ti alloys for tribological purposes has focused on these specific strategies: biomedical coatings, mechanical surface treatment, and the design strategies for alloys and titanium matrix composites. The current review has examined these strategies in terms of their formulation, manufacturing techniques, tribological testing parameters, and characterization methodologies. This final section provides future research directions and suggestions regarding the discussed strategies for improving tribological behaviour of Ti alloys used for biomedical applications.

The tribological testing protocols for alloys and biomedical elements are yet to be well established. The majority of researchers rely on prior studies and their own experience, often neglecting limb-specific tests that consider the unique human limb kinematics and biology. It is imperative that comprehensive protocols for titanium alloys are developed. While conventional load-cell-based wear testers are invaluable, advanced techniques such as EBSD and HRTEM should be integrated to facilitate detailed examinations. It is also concerning that many studies lack statistical tools (e.g., ANOVA) to evaluate parameter effects. Furthermore, machine learning methods are not utilised despite their large potential. It is therefore essential that future research addresses these gaps; optimising tribological parameters for human limb applications and incorporating comprehensive design, implementation, and prediction stages.

A variety of techniques including PEO, anodization, vapor deposition, sol-gel, thermal spray, laser cladding, and nitriding have been demonstrated to enhance the durability of titanium alloys and reduce friction. PEO, laser cladding, and nitriding are prominent techniques, but PEO coatings face issues with defects affecting wear resistance. Further research is required on novel coatings and uniformity for laser cladding. Nitriding improves tribological properties with protective coatings, but studies mostly focus on conventional titanium alloys, indicating a need to explore new-generation alloys.

The tribological performance of biomedical Ti alloys can be enhanced through the application of shot peening, laser peening, and surface mechanical attrition. However, further research is required to determine the optimal processing parameters for achieving the best results. In recent investigations, finite element modeling helps with strain and stress predictions but lacks tribological property forecasts. Combining these treatments with coatings shows promise, indicating increased future research in this area.

The limitations of titanium matrix biomedical composites highlight the need for further investigation in tribological studies, particularly with regard to the diverse types of titanium alloys, reinforcement elements, and manufacturing methods. The majority of research has concentrated on the characteristics of the reinforcement components, rather than on the production methodologies. Significant gaps exist in the understanding of advanced process causation, particularly in the areas of parametric optimisation and machine learning. The traditional Ti grade 2 and Ti6Al4V alloys have been the subject of extensive research. This highlights the necessity for a comprehensive innovative approach to the design and manufacture of titanium matrix composites.

Author contributions

EA: Conceptualization, Formal Analysis, Investigation, Methodology, Validation, Writing–original draft, Writing–review and editing. MA: Conceptualization, Formal Analysis, Investigation, Methodology, Validation, Visualization, Writing–original draft, Writing–review and editing. YY: Conceptualization, Formal Analysis, Investigation, Methodology, Validation, Writing–original draft, Writing–review and editing. MG: Formal Analysis, Methodology, Project administration, Supervision, Writing–original draft, Writing–review and editing. BY: Formal Analysis, Methodology, Project administration, Supervision, Writing–original draft, Writing–review and editing. EA: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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