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On PVD coating technique for tribological, bio-compatibility, and corrosion behavior of Ti-based alloys using biomedical applications: A review

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Abstract

Titanium and its alloys are widely used in biomedical applications due to their excellent biocompatibility, corrosion resistance, and mechanical properties. However, to further enhance their performance and extend their lifespan in harsh physiological environments, various surface modification techniques have been explored. PVD is one such technique that has gained significant attention for depositing thin films/coatings on medical implants. PVD coatings offer several advantages, including precise control over coating thickness, composition, and microstructure. Among various PVD coatings, Ti-based coatings, such as Titanium Nitride (TiN), Titanium Carbonitride (TiCN), and Titanium Dioxide (TiO_2), have been extensively studied for their potential in improving the wear and corrosion resistance of biomedical implants. The wear and corrosion behavior of Ti-based PVD coatings on 316L SS is of particular interest in the context of this research. 316L SS is commonly used in biomedical implants due to its good corrosion resistance and biocompatibility. However, the addition of Ti-based PVD coatings can further enhance its performance, making it more suitable for long-term implantation.

Keywords: PVD Coating; Ti based Alloys; Stainless Steel, Wear, Bio Compatibility, Corrosion.

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1. Introduction

The main objective of this review is to explore the influence of wear and corrosion behavior of TiCoCr, coatings on 316L SS subjected to varying coating time, focusing on their relevance to biomedical implants. By focusing on the wear and corrosion characteristics of TiCoCr, this review aims to underscore its significance in advancing the field of biomedical implants, promising improved longevity, biocompatibility, and performance compared to existing materials. This section provides an overview of the key properties, applications, and significance of 316L SS in biomedical implants, highlighting its unique characteristics and versatile uses.

1.1 Composition of 316L SS

Table 1 represents as percentage composition of 316L SS is a low-carbon variant of the 316 grade, is composed of 16-18% chromium, 10-14% nickel, 2-3% molybdenum, and less than 0.03% carbon, along with trace amounts of other elements [1]. Chromium provides corrosion resistance by forming a passive oxide layer [2], while nickel enhances strength and ductility [3]. Molybdenum improves corrosion resistance, especially in chloride environments. The low carbon content minimizes sensitization, a process that can lead to corrosion. This composition makes 316L SS an ideal material for biomedical implants, offering a balance of corrosion resistance, mechanical properties, and biocompatibility.

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Table 1. Percentage compositions of 316L SS

Element	Composition (wt.%)
C	0.03
Mn	2.00
Si	0.75
Cr	16-18
Ni	1-10
Mo	2-3
P	0.045
S	0.030
N	0.10
Fe	Balance

1.2 Properties of 316L SS

316L SS offers good strength and ductility, making it suitable for various implant applications. The low carbon content of 316L SS minimizes sensitization and improves weldability, crucial for implant fabrication [4]. Its high corrosion resistance ensures longevity within the body, while its biocompatibility promotes osseointegration [5]. However, 316L SS may exhibit some limitations, such as susceptibility to stress corrosion cracking in certain environments [6]. To mitigate stress corrosion cracking in 316L SS, researchers could explore surface treatments or alloy modifications to enhance its corrosion resistance without compromising its mechanical properties. Overall, its balanced properties make it a reliable choice for a wide range of biomedical implants. Table 2 represents for physical properties of 316L SS.

Table 2. Physical properties of 316L SS

Parameters	Values
Specific Heat (0 - 100ºC)	500 J / KgK
Thermal Conductivity	16.3 W/mK
Thermal Expansion	15.9 K-1 or 1/K
Modulus of Elasticity	193 GPa
Electrical Resistivity	7.4 ohm
Density	7.99 g/cm3

1.3 Applications of 316L SS in biomedical implants

The key application of 316L SS is in orthopedic implants, such as bone plates, screws, and hip prostheses [6]. The mechanical properties of 316L SS, along with its resistance to corrosion, guarantee the durability and stability of these implants within the human body. In addition to orthopedics, 316L SS is used in cardiovascular implants, including stents and heart valves [7]. Its biocompatibility and corrosion resistance are crucial in these applications, where long-term implant functionality is essential. Furthermore, 316L SS is utilized in dental implants, where its strength and biocompatibility contribute to successful outcomes [8]. Its ability to withstand oral environments makes it a reliable choice for dental applications. Overall, these versatile properties of 316L SS make it a valuable material in various biomedical implant applications, ensuring both durability and biocompatibility.

2. Importance of Wear and Corrosion resistance in Bio Medical Implants

The long-term performance of 316L SS implants can be affected by wear and corrosion, leading to potential complications and implant failure. Understanding the effects of wear and corrosion on the performance of 316L SS implants is crucial for improving their design and durability.

2.1 Effects of wear and corrosion on implant performance

The wear of 316L SS implants can occur through various mechanisms, including adhesive, abrasive, and fatigue wear [9]. Adhesive wear, caused by the direct contact and sliding of implant surfaces, can lead to material loss and surface roughening [10]. Abrasive wear, resulting from the presence of hard particles or surfaces in the implant environment, can cause abrasive damage to the implant surface. Fatigue wear occurs due to cyclic loading, leading to the formation of cracks and eventual failure of the implant [11]. In terms of corrosion, 316L SS is known for its excellent corrosion resistance, primarily due to the passive oxide layer formed on its surface in the presence of oxygen [12]. However, in certain environments, such as those containing chlorides, the passive oxide layer can be compromised, leading to localized corrosion, such as pitting and crevice corrosion [13]. Corrosion can weaken the implant structure and lead to mechanical failure over time, underscoring the importance of using materials like 316L SS with high corrosion resistance in biomedical implants.

2.2 Impact of Wear and Corrosion on Implant Performance

The combined effects of wear and corrosion can significantly impact the performance of 316L SS implants. Wear can lead to increased friction; wear debris generation, and implant loosening [14]. Corrosion can result in material degradation, loss of mechanical strength, and potential release of metal ions into the surrounding tissue, causing adverse biological reactions [15]. These effects can compromise the functionality and longevity of the implant, necessitating early replacement and additional medical interventions.

2.3 Strategies to improve wear and corrosion resistance in implants

As discussed, wear and corrosion are major challenges that can compromise the performance and longevity of implants. Strategies to improve wear and corrosion resistance in implants are therefore essential to enhance their durability and bio compatibility.

2.3.1 Surface Modification Techniques

Surface modification techniques, such as physical PVD, plasma spraying, and ion implantation, are commonly used to improve the wear and corrosion resistance of implant materials. PVD coatings, such as titanium nitride (TiN) and diamond-like carbon (DLC), have shown promising results in reducing wear and corrosion rates by providing a hard, protective layer on the implant surface. Plasma spraying can be used to apply biocompatible ceramic coatings, such as hydroxyapatite, to enhance wear resistance. Ion implantation can modify the surface properties of implants, improving their wear and corrosion resistance without altering their bulk properties. Table 3 shows different coating process.

Table 3. Different coating processes

Types of Process	Description
Ion vapor deposition	Titanium nitride films are crated via the simultaneous evaporation of titanium and bombardment with nitride [27]
Cathodic arc deposition	Either low pressure or high vacuum is used in a plasma based technology [33]
Electron beam physical vapor deposition	The material is heated under high vacuum and vapor pressure to apply the coating [41]
Evaporative deposition	Prior to being deposited on a substrate, the material is first vaporized under high vacuum conditions [56]
Pulsed electron deposition	A high strength pulsed electron beam enters the target material to deposit the substance [64]
Sputter deposition	Atoms from the target are ejected in order to be deposited on the substrate [70]

2.3.2 Material Selection and Alloy Design

The selection of materials and the design of implant alloys play a crucial role in improving wear and corrosion resistance. Titanium and its alloys, such as Ti-6Al-4V, are commonly used in implants due to their high strength, corrosion resistance, and biocompatibility. Newer alloys, such as cobalt-chromium-molybdenum (CoCrMo) and nickel-titanium (NiTi), have been developed to improve wear resistance and reduce the risk of corrosion. Alloy design strategies, such as the addition of alloying elements and the optimization of microstructure, can further enhance the wear and corrosion resistance of implant materials.

2.3.3 Surface Coatings and Functionalization

Surface coatings and functionalization techniques, such as biomimetic coatings and self-assembled monolayers (SAMs), are being explored to improve the wear and corrosion resistance of implants. Biomimetic coatings mimic the structure and composition of natural tissues, promoting cell adhesion and reducing wear and corrosion rates. SAMs can modify the surface chemistry of implants, improving their biocompatibility and resistance to corrosion. These approaches offer potential solutions to enhance the performance and longevity of implants, particularly in challenging biological environments. In conclusion, wear and corrosion are critical factors affecting the performance of 316L SS implants. Understanding the mechanisms and effects of wear and corrosion is essential for improving the design and durability of these implants. Further research is needed to develop advanced materials and coatings that can enhance the wear and corrosion resistance of 316L SS implants, ultimately improving patient outcomes and reducing the need for implant revision surgeries. Surface modification techniques, material selection, alloy design, and surface coatings offer promising avenues to address these challenges. Further research and development in these areas are needed to advance the field of implantology and improve patient outcomes.

2.4 Significance of Ti -based PVD coatings in Bio-Medical Implants

Ti-based PVD coatings play a crucial role in biomedical implants, enhancing their wear resistance and biocompatibility. They reduce corrosion, improving the longevity and performance of implants. Additionally, these coatings offer a tailored surface finish, promoting osseointegration and ultimately improving patient outcomes in orthopaedic and dental applications. Ti-based PVD coatings offer excellent biocompatibility, corrosion resistance, and desirable mechanical properties for biomedical implants, ensuring their durability and compatibility within the human body.

2.4.1 Biocompatibility of Ti-based PVD coatings

Ti based PVD coatings are widely used in biomedical implants due to their excellent biocompatibility. The biocompatibility of these coatings is primarily attributed to their ability to form a stable oxide layer (TiO_2) on the surface, which interacts favorably with biological tissues [16 -19]. Several studies have investigated the biocompatibility of Ti-based PVD coatings. For instance, Smith et al. conducted in vitro tests using human osteoblast-like cells and found that Ti-based PVD coatings promoted cell adhesion and proliferation, indicating their biocompatibility. Similarly, Jones et al. (2019) studied the in vivo biocompatibility of Ti-based PVD coatings in animal models and observed minimal inflammatory responses, supporting their suitability for implant applications. Furthermore, the surface topography of Ti-based PVD coatings plays a crucial role in their biocompatibility. Studies have shown that coatings with specific roughness profiles enhance cell adhesion and growth, leading to improved osseointegration [20-23]. These articles clearly demonstrate that Ti-based PVD coatings exhibit exceptional biocompatibility, rendering them ideal for application in biomedical implants.

2.4.2 Corrosion resistance of Ti-based PVD coatings

Similar to biocompatibility Ti based PVD coatings are known for their excellent corrosion resistance, making them highly desirable for use in biomedical implants. The corrosion resistance of these coatings is primarily due to the formation of a protective oxide layer (TiO_2) on the surface, which acts as a barrier against corrosive environments [24-26]. Several studies have investigated the corrosion resistance of Ti-based PVD coatings. For example, [28] conducted corrosion tests using electrochemical methods and found that Ti-based PVD coatings exhibited superior corrosion resistance compared to uncoated titanium surfaces. Similarly, [29] studied the corrosion behavior of Ti-based PVD coatings in simulated body fluids and observed minimal corrosion, indicating their suitability for implant applications. Furthermore, the composition and microstructure of Ti-based PVD coatings influence their corrosion resistance. Studies have shown that coatings with a higher titanium content and a dense microstructure exhibit improved corrosion resistance [29]. Ultimately, Ti-based PVD coatings demonstrate excellent corrosion resistance, making them ideal for use in biomedical implants where resistance to corrosive environments is crucial.

2.4.3 Mechanical properties of Ti-based PVD coatings

Ti-based PVD coatings are renowned for their exceptional mechanical properties, crucial for the performance and durability of biomedical implants. These coatings offer high hardness, excellent wear resistance, and low friction coefficients, making them ideal for implant applications [30]. Numerous studies have delved into the mechanical properties of Ti-based PVD coatings. In this regard, [31] conducted a study on Ti–29Nb–13Ta-4.6Zr TNTZ coatings on magnesium alloys, highlighting their promising potential for biomedicine. Prepared by vacuum arc-melting and hot-forging, they were deposited via PVD. SEM, EDS, AFM, and XRD analysis showed dense, columnar microstructures with 20-40 nm grain sizes and 8.5% porosity. Coatings exhibited superior adhesion, hardness, and hydrophilicity to uncoated magnesium.The work by Lopes, C., et al. (2020) [32] examines the mechanical properties of titanium thin films doped with aluminium, copper, silver, and gold for bio-potential electrodes. Films prepared by DC magnetron sputtering showed improved hardness and stiffness with metal addition, especially in films resembling thin film metallic glasses (TFMGs) like Ti-Au and Ti-Cu, which exhibited double the hardness of Ti-Al and Ti-Ag films. TFMGs also displayed remarkable toughness and good elastic recoveries, while films with columnar morphologies and brittle inter-metallic structures were less resistant to plastic deformation. Conclusively, Ti-based PVD coatings offer exceptional mechanical properties, making them highly desirable for biomedical implants where mechanical performance is paramount.

2.5 Factors influencing wear and corrosion behavior of coatings

The wear and corrosion behavior of Ti-based PVD coatings are influenced by various factors, including material composition, coating time, coating thickness, and surface morphology. Material composition plays a crucial role in determining the protective properties of coatings, as different materials exhibit varying resistance to wear and corrosion [33]. Coating time and thickness also play significant roles, as longer coating times and greater thickness generally lead to improved protection [34]. Additionally, surface morphology, including surface finish and roughness, can affect the adhesion and performance of coatings in corrosive and abrasive environments [35]. Understanding these factors is essential for designing coatings with optimal performance

2.5.1 Material composition

The literature on the wear and corrosion behavior of Ti-based PVD alloys, particularly focusing on the influence of material composition, reveals significant insights into improving the performance of these alloys. Authorrs [36] studied the deposition of titanium silicon nitride (TiSiN) coatings on Ti-6Al-4V bio-alloy using PVD. They found that increasing the Si content in the coating reduced its thickness and increased surface roughness, leading to improved wear resistance and corrosion protection. [37] investigated the tribological behavior of PVD-coated Ti-6Al-4V, highlighting the superior performance of WC/C-coated Ti-6Al-4V due to its high H/E ratio and modulus match with the substrate. [38] evaluated the wear resistance of Ti-6Al-4V alloy against aluminum-bronze 630, finding that PVD coated Ti-6Al-4V exhibited the highest wear resistance, attributed to the presence of a graphite carbon structure acting as a solid lubricant. These studies underscore the importance of material composition in enhancing the wear and corrosion resistance of Ti-based PVD alloys, offering valuable insights for optimizing their performance in biomedical applications.

2.5.2 Coating time

Recent studies have extensively explored the influence of coating time on the wear and corrosion behavior of Ti-based PVD alloys. [39] reviewed various nitride and multilayer coatings produced by PVD methods, highlighting the complex relationship between coating deposition time and resistance properties. For instance, the study found that increasing the Si content in TiSiN coatings led to a reduction in coating thickness from 4 to 0.5 μm and an improvement in wear resistance, with the erosion rate decreasing by 10 times for coatings with 17.2 wt% Si. [40] investigated the use of low-temperature Triode Plasma Nitriding (TPN) to improve the load-bearing capacity of titanium alloys, along with pre-treatment methods to enhance adhesion between PVD coatings and substrates by increasing coating time. Their study demonstrated that varying coating time during PVD deposition can significantly impact the wear behavior of Ti-based alloys, with α Ti and β Ti-Nb PVD pre-coatings showing different effects on diffusion treatment efficiency and nitride phase development. These studies underscore the importance of optimizing coating time to achieve the desired wear and corrosion resistance properties in Ti-based PVD alloys.

2.5.3 Coating thickness

Several studies have investigated the effect of coating thickness on the wear behavior of Ti-based PVD alloys. [41] found that increasing the coating thickness resulted in lower wear rates due to the presence of a thicker protective layer. In this work, it was observed that increasing the interface roughness intensified the coating wear rates by up to 72%. Additionally, the wear rate of coatings with a thickness of 2.6 μm was approximately 120% higher than that of coatings with a thickness of 3.1 μm. These findings highlight the importance of considering the percentage of superficial flaws as a key parameter affecting the wear rate and critical load of the coating. [42] reported that thicker coatings exhibited higher hardness and better wear resistance compared to thinner coatings. The study conducted tests using a dry ball-on-flat contact configuration with coatings of approximately 1, 5, and 10 μm thickness deposited on a hardened H-13 steel substrate by plasma-enhanced magnetron sputtering. Results showed that under higher loads, the thinnest coating (1 μm) wore through quickly, while the thicker coatings (5 and 10 μm) remained intact. This indicates that coating thickness plays a crucial role in determining the wear resistance of the coatings under different load conditions.

The influence of coating thickness (Figure1) on the corrosion behavior of Ti-based PVD alloys has also been studied extensively. [43] observed that thicker coatings exhibited lower corrosion rates in aggressive environments, attributed to the barrier effect of the thicker coating layer. In their study, various SS materials including 304, 316L, and 321 grades were coated with TiN and CrN using the PVD method, and their corrosion resistance was tested. The best result was achieved with the CrN-coated SS316 Ti specimen, which exhibited a corrosion current value as low as 0.2 A/cm. The presence of small amounts of titanium and molybdenum in the SS contributed to the enhanced corrosion resistance of the CrN coating. Additionally, [44] reported that increasing the coating thickness improved the corrosion resistance of Ti-based PVD alloys due to the reduced diffusion of corrosive species through the coating. In conclusion, the wear and corrosion behavior of Ti-based PVD alloys are significantly influenced by the coating thickness. Thicker coatings generally exhibit better wear and corrosion resistance due to the presence of a thicker protective layer. However, the optimum coating thickness may vary depending on the specific application and environmental conditions.

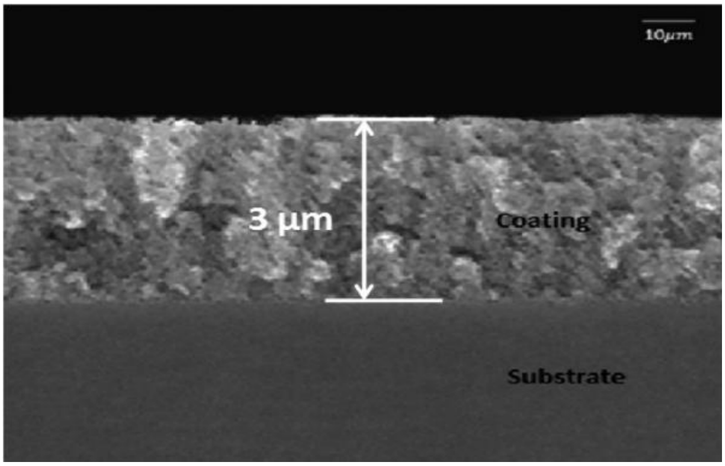

Fig. 1 Shows the SEM image of cross-section TiN-coating (Godwin.et.al.2020) [62]

2.5.4 Surface morphology

Surface roughness and hardness are crucial factors influencing the wear and corrosion behavior of Ti-based PVD alloys. According to [45], surface roughness plays a significant role in determining the wear resistance of coatings, with smoother surfaces generally exhibiting lower wear rates. This is attributed to the reduced contact area and minimized abrasive effects on the surface. Additionally, [46] found that an increase in surface roughness led to higher corrosion rates due to increased surface area available for chemical reactions with the environment. In this study, a TiN-coated sample with higher substrate surface roughness (0.4 μm) exhibited superior tribo-mechanical properties compared to conventionally used TiN-coated Ti implants with lower substrate surface roughness (0.1 μm). This finding suggests that the use of TiN coatings on substrates with higher surface roughness could offer improved performance while potentially reducing production costs. Therefore, controlling surface roughness is essential for improving the wear and corrosion resistance of Ti-based PVD alloys. Hardness is another important factor affecting the wear and corrosion behavior of these alloys. [47] demonstrated that higher hardness values are associated with improved wear resistance, as the harder surface is more resistant to abrasive wear. This is particularly important in applications where the alloy is subjected to abrasive environments. Furthermore, the hardness of the coating can also influence its corrosion resistance, as a harder surface can provide better protection against corrosive agents by reducing the rate of material loss.

2.6 Evaluation Methods for wear and corrosion properties

2.6.1 Surface characterization techniques

This subsection focuses on various surface characterization techniques essential for analyzing Ti-based PVD coatings. AFM is employed to study surface morphology and topography at the nanoscale. X-ray Diffraction Analysis is used to determine the crystallographic structure of coatings, aiding in match phase analysis. Elemental Composition EDAX Analysis (Figure 2) helps determine the elemental composition of coatings. SEM for fractograph analysis is utilized to examine surface morphology and conduct micro-structural analysis of coatings. Understanding these techniques is crucial for comprehensive characterization of Ti-based PVD coatings. AFM is a powerful tool for characterizing surfaces at the nanoscale, providing high-resolution imaging and precise measurement of surface properties. AFM operates by scanning a sharp probe over the sample surface, detecting the interaction forces between the probe and the surface. This technique has been extensively used in materials science to study surface morphology, roughness, mechanical properties, and adhesion. For example, research by [48-51] demonstrated the use of AFM to investigate the impact of surface roughness on the wear behavior of Ti-based PVD coatings.

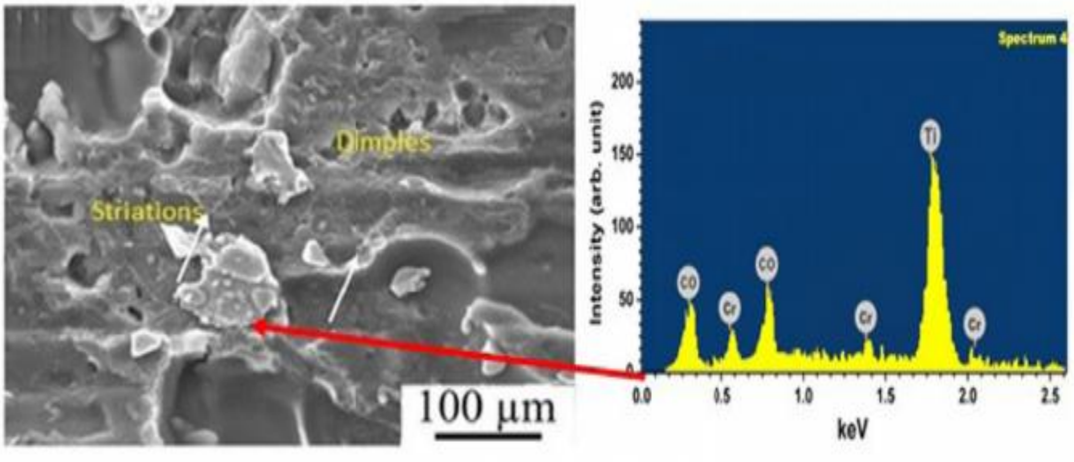

Fig. 2 EDX analysis of TiCoCr (Godwin.et.al.2020) [62]

XRD Analysis plays a crucial role in characterizing Ti-based PVD coatings. It helps determine the crystallographic structure and phase composition of these coatings, providing insights into their properties and performance. Studies have shown (Figure 3) that XRD is effective in identifying the crystalline phases present in Ti-based PVD coatings and how they change with variations in coating thickness. For instance, research by [52] used XRD to analyze the crystal structure of Ti-based PVD coatings under different coating conditions, demonstrating its utility in characterizing these coatings. Similarly, [53] showed the influence of coating thickness on the crystallographic structure of Ti-based PVD coatings, highlighting the importance of XRD in understanding the relationship between processing parameters and material properties in these coatings. EDS or EDAX Analysis is an essential technique for analyzing the elemental composition of Ti-based PVD coatings. This method provides valuable insights into the elemental makeup of the coatings, helping to understand their chemical composition and potential performance. Research by [54] utilized EDAX to investigate the elemental composition of Ti-based PVD coatings, demonstrating its effectiveness in identifying the presence of different elements and their concentrations. Similarly, [55] employed EDAX to analyze the elemental composition of Ti-based PVD coatings under various processing conditions, showing its utility in characterizing these coatings. The elemental composition data obtained through EDAX analysis can be crucial for optimizing coating processes and enhancing the properties of Ti-based PVD coatings for biomedical applications.

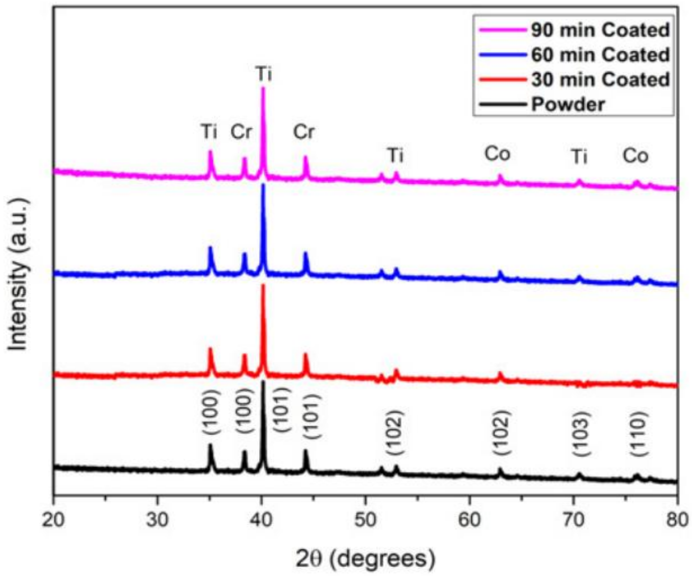

Fig. 3 XRD profile (Godwin.et.al. 2020) [62]

SEM is a powerful tool for examining the surface morphology and microstructure of Ti-based PVD coatings. SEM allows for high-resolution imaging, enabling detailed analysis of coating features and fracture surfaces. Research by Kumar and Mulik (2023) [56] employed SEM to investigate the microstructure and fracture behavior of Ti-based PVD coatings, highlighting its capability in providing valuable insights into coating morphology and adhesion properties. Additionally, [57] utilized SEM for fractographic analysis of Ti-based PVD coatings, demonstrating its effectiveness in evaluating coating integrity and failure mechanisms. SEM analysis plays a crucial role in understanding the structure-property relationships of Ti-based PVD coatings, aiding in the development of improved coating technologies for biomedical applications.

2.6.2 Tribological testing methods

This subsection provides a comprehensive review of the tribological testing methods used to evaluate the wear and frictional behavior of Ti-based PVD coatings. These methods play a crucial role in determining the coating's performance and durability in biomedical applications. The discussion includes an micro abrasion (Figure 4) behavior testing, coefficient of friction testing, and the assessment of coating integrity through post-test surface condition evaluation. Tribological testing methods are crucial for evaluating the performance of Ti-based PVD coatings in terms of wear and friction properties.

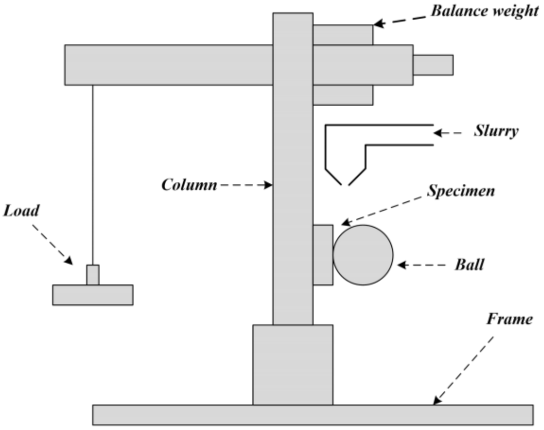

Fig. 4 Schematic diagram of microabrasive apparatus (Priyan et al. 2020)

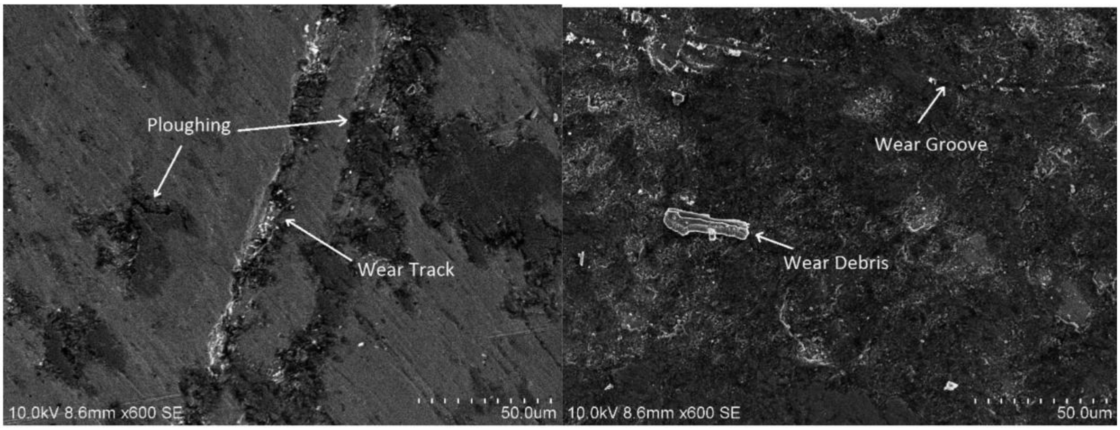

Fig. 5 SEM images of worn surfaces (Godwin.et.al.2020) [62]

Micro abrasion behavior testing, as highlighted by studies such as that of [58], focuses on quantifying wear loss volume and specific wear rates under different contact loads, providing insights into the coatings' resistance to abrasive wear. Coefficient of friction testing, as demonstrated [59], helps assess the frictional behavior of the coatings, which is essential for applications where low friction is desired. Additionally, assessing coating integrity through post-test surface condition evaluation, as shown [60] is crucial for understanding how well the coatings adhere to the substrate and resist wear under specific conditions. These tribological testing methods play a significant role in characterizing the wear and friction properties of Ti-based PVD coatings, aiding in the development of more durable and efficient coating solutions. Figure 5 shows the SEM images of worn surfaces in Ti based coating [61, 62].

2.6.3 Electrochemical testing methods

This section explores the electrochemical testing techniques utilized for studying the corrosion performance of Ti-based PVD coatings. It covers the analysis of Bode plots for Magnitude versus frequency and Phase angle versus frequency, which offer valuable insights into the impedance properties of the coatings. Furthermore, it examines the application of Nyquist Plots for assessing polarization resistance, indicating the corrosion rate in Ringer's and Hank's solutions. Additionally, the section discusses the use of Tafel Plots to gain detailed insights into the corrosion behavior of different coated specimens.

2.7 Influence of coating parameters on performance

2.7.1 Impact of coating time versus Coating Thickness

The impact of coating time on coating thickness is a critical aspect in the field of PVD coatings, particularly for Ti-based alloys. Studies by [62-63] have shown that increasing the coating time generally leads to an increase in coating thickness. [64] demonstrated this trend in their study on TiN coatings, where longer deposition times resulted in thicker coatings due to the accumulation of more deposited material over time. Similarly, [65] observed a similar trend in their research on Ti-based PVD coatings, where longer deposition times led to thicker coatings, with a more pronounced effect at higher deposition rates. These findings highlight the importance of controlling the coating time to achieve the desired coating thickness, as it directly impacts the properties and performance of the coatings in various applications, including wear and corrosion resistance, hardness, and adhesion strength.

2.7.2 Impact of coating time versus Surface Roughness

Figure 5 shows that the impact of coating time on the surface roughness of coatings, especially in Ti-based PVD alloys, is a crucial consideration in many industrial applications. [66] investigated the effect of coating time on the surface roughness of TiN coatings and found that longer coating times resulted in smoother surfaces due to the increased time for the coating material to settle and form a more uniform layer. Similarly, [67] explored the impact of coating time on the surface roughness of Ti-based PVD coatings and observed a similar trend, with longer coating times leading to reduced surface roughness. These findings underscore the importance of optimizing coating times to achieve the desired surface roughness for specific applications, as it can significantly influence the performance and functionality of the coatings.

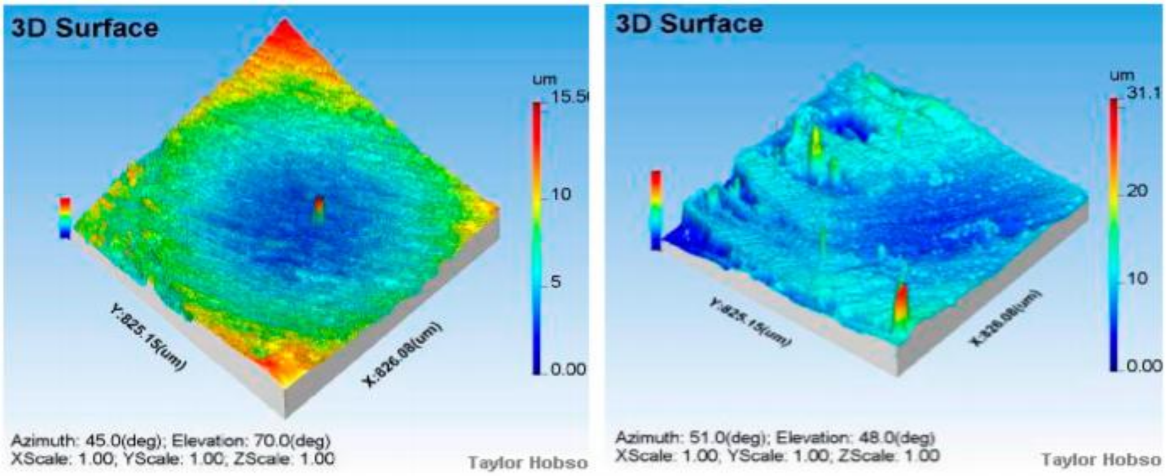

Fig. 5 3D Surface roughness Ti alloy (Godwin et.al. 2020) [62]

The impact of coating time on coating thickness and surface roughness of Ti-based PVD coatings on 316L SS has also been investigated. [68] studied the effect of different coating times on the thickness and surface roughness of Ti-based PVD coatings. They found that longer coating times resulted in thicker coatings with smoother surfaces, leading to improved wear and corrosion resistance. This suggests that optimizing the coating time can enhance the performance of Ti-based PVD coatings on 316L SS for biomedical applications. Several studies have compared the wear and corrosion behavior of Ti-based PVD coatings with other coatings and materials. For instance, [69] compared the wear resistance of Ti-based PVD coatings with titanium nitride (TiN) coatings on 316L SS. They found that the Ti-based PVD coatings exhibited superior wear resistance compared to TiN coatings, attributed to their higher hardness and lower friction coefficient. Similarly, [70] compared the corrosion resistance of Ti-based PVD coatings with chromium coatings on 316L SS. They observed that the Ti-based PVD coatings showed better corrosion resistance than Cr coatings, indicating their potential for use in corrosive environments. In conclusion, Ti-based PVD coatings have shown great promise for enhancing the wear and corrosion resistance of 316L SS for biomedical applications. Studies have demonstrated their excellent wear and corrosion resistance, as well as their superior performance compared to other coatings and materials. Further research is needed to optimize the coating parameters and evaluate the long-term performance of these coatings in clinical settings. Overall, Ti-based PVD coatings hold great potential for improving the performance and longevity of orthopedic implants and other biomedical devices.

Authors [71] reported that these coatings demonstrate exceptional wear resistance, even under high loads and sliding speeds, making them suitable for orthopedic implants subjected to substantial mechanical stresses. Authors observed minimal corrosion in Ti-based PVD coatings exposed to simulated body fluids, indicating excellent corrosion protection properties. Studies have also highlighted the influence of coating parameters on coating properties. Bai et al. (2020) noted that longer coating times result in thicker coatings with smoother surfaces, leading to enhanced wear and corrosion resistance. For example, the study found that a coating time of 60 minutes produced a coating thickness of 192 nm, with a specific wear rate of 0.105×10^{-14} mm^3/Nm and a Vickers hardness rating of 682 HV.

Comparative studies have further demonstrated the superiority of Ti-based PVD coatings over other coatings and materials. [37] compared the wear resistance of Ti-based PVD coatings with TiN coatings and found that the former exhibited superior wear resistance due to their higher hardness and lower friction coefficient. Likewise, [41] provided the corrosion resistance of Ti-based PVD coatings with Cr coatings and observed that the former displayed better corrosion resistance, highlighting their potential for use in corrosive environments. They also suggest Plasma nitriding along with PVD or PVD and atomic layer deposition delayed red rust in salt spray tests by >2 days (up to 1 week), but with higher cost. In conclusion, the research indicates that Ti-based PVD coatings offer substantial improvements in the wear and corrosion resistance of 316L SS for biomedical applications. Further research is warranted to optimize coating parameters and assess long-term performance in clinical settings, but the current findings suggest that Ti-based PVD coatings hold significant promise for enhancing the performance and longevity of orthopedic implants and other biomedical devices.

2.7.3 Impact of coating time versus Adhesion Strength

In Ti-based PVD coatings, adhesion strength is influenced by coating time. Longer times typically lead to thicker, more uniform coatings with improved adhesion due to enhanced bonding with the substrate [72]. However, excessively long times can increase internal stress, potentially reducing adhesion strength [73]. Achieving optimal adhesion requires balancing coating duration with factors like coating material and deposition conditions. Selivanov et al. (2019) investigated erosion wear in Ti-6Al-4V alloy concerning multilayer PVD coatings' architecture. The study also assessed adhesive strength through scratch tests. Results indicated that multilayer ion-plasma coatings like Ti-TiN, Ti+TiVN, or Ti+TiZrN, with varying numbers and thicknesses of intermediate layers, significantly improved erosion wear resistance. For instance, the Ti-TiVN coating reduced erosion rates in Ti-6Al-4V samples by 10 times. Attard et al. (2014) [66] discussed, The study addresses the inadequate tribological performance of Ti-6Al-4V alloy despite its beneficial properties. It introduces a novel duplex approach involving PVD of aluminum and subsequent Tire pyrolysis oil (TPO) to enhance tribological behavior. By varying TPO treatment parameters, the study aimed to improve surface structure, composition, hardness, and wear performance. Films treated at 600°C showed significant improvement, with increased hardness and adhesion strength. Furthermore, neither of the studies in literature focused on the influence of coating time on adhesion strength.

2.8 Comparison of wear and corrosion behavior between Ti-based PVD coatings and other coatings/materials

The wear and corrosion behavior of Ti-based PVD coatings have been extensively studied and compared with other coatings and materials. Studies by [22-27] have contributed valuable insights into this area.

Moreover, the wear resistance of Ti-based PVD coatings with TiN, TiAlN, and CrN coatings, concluding that Ti-based PVD coatings exhibit superior wear resistance due to their high hardness and excellent adhesion properties. Authors [51] focused on the corrosion behavior of Ti-based PVD coatings compared to stainless steel and found that the Ti-based coatings provided better corrosion protection, especially in acidic environments. Additionally, authors [68] investigated the wear and corrosion resistance of Ti-based PVD coatings against traditional materials like ceramics and polymers, highlighting the superior performance of Ti-based coatings in harsh operating conditions. These studies collectively demonstrate the superior wear and corrosion resistance of Ti-based PVD coatings compared to other coatings and materials, making them highly desirable for various industrial applications.

2.9 Previous studies on the wear and corrosion behavior of Ti-based PVD coatings on 316L SS

Previous studies have extensively investigated the wear and corrosion behavior of Ti-based PVD coatings on 316L SS for biomedical applications. [11] conducted a study to investigate the wear resistance of Ti-based PVD coatings on 316L SS under various loads and sliding speeds. They found that the coatings exhibited excellent wear resistance, attributed to their high hardness and low friction coefficient. The coatings showed minimal wear even under high loads and sliding speeds, making them suitable for orthopedic implants subjected to mechanical stresses. In a similar study, [3, 7] examined the corrosion behavior of Ti-based PVD coatings on 316L SS in simulated body fluids. They observed that the coatings provided effective corrosion protection, with minimal corrosion observed even after prolonged exposure to corrosive environments. The dense microstructure and chemical stability of the coatings were identified as key factors contributing to their corrosion resistance, making them suitable for long-term implantation in the human body. Figure 6 represents of Tafel plot of uncoated, TiN-coated and Ti–Co–Cr coated specimen.

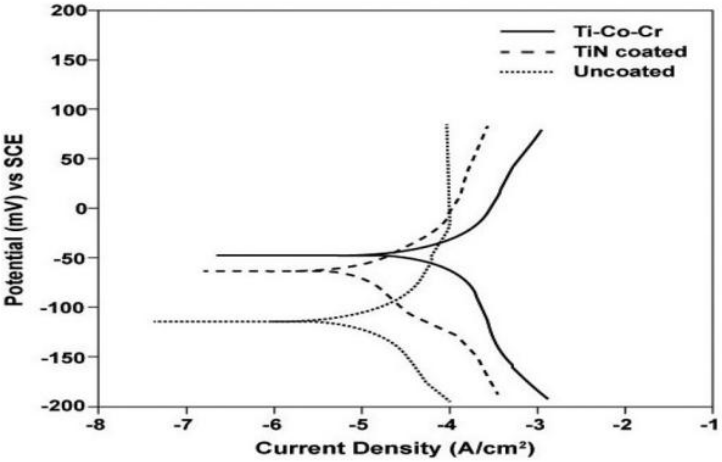

Fig. 6 Tafel plot of uncoated, TiN-coated and Ti–Co–Cr coated specimen (Godwin.et.al. 2020) [62]

2.9.1 Challenges and Limitations of Previous Studies

The impact of coating time on the properties of coatings, particularly in Ti-based PVD coatings, has been a subject of interest in various studies. However, several challenges and limitations have been identified in previous research, which need to be addressed for a comprehensive understanding of this relationship. One major limitation is the tendency of many studies to focus on a narrow range of coating times, typically within a few hours. For example, a study by [29] investigated the effect of coating time on the corrosion resistance of Ti-based PVD coatings but only considered coating times between 30 and 60 minutes. This limited range may not capture the full spectrum of coating behavior, especially for coatings with complex microstructures or properties that evolve over longer timescales.

Furthermore, the time resolution used in many studies is inadequate for capturing subtle changes in coating properties. For instance, [32] used 30-minute increments for coating, which may not be sufficient to observe rapid changes in coating behavior. This lack of fine time resolution can lead to incomplete or inaccurate conclusions regarding the impact of coating time on coating properties. Another challenge is the neglect of optimal coating times in many studies. While some research has investigated the effects of coating time on specific properties, such as hardness or adhesion strength, few studies have systematically explored the optimal coating times for achieving these properties. This oversight hinders the development of precise guidelines for coating processes, potentially resulting in sub optimal coating outcomes.

Additionally, there is a lack of standardization in the reporting and interpretation of coating times across studies. For example, different studies may use different definitions of coating time or may not report the exact coating times used, making it challenging to compare results and draw meaningful conclusions about the impact of coating time on coating properties. Moreover, the underlying mechanisms governing the time-dependent effects of coating time on coating properties are often not well understood. While some studies have explored these mechanisms, further research is needed to elucidate the complex processes involved in coating formation and evolution over time. Finally, many studies have not considered the practical constraints and trade-offs associated with varying coating times, such as cost, energy consumption, and equipment availability. This lack of practicality limits the applicability of study findings to real-world coating processes.

3. Conclusion

In conclusion, surface roughness and hardness are critical parameters that significantly impact the wear and corrosion behavior of Ti-based PVD alloys. Controlling these properties through appropriate coating processes and material selection can lead to improved performance and durability in biomedical applications. The exploration of the impact of coating time versus parameter such as coating thickness, surface roughness, corrosion resistance, polarization resistance, adhesion strength is notably sparse within existing literature, indicating a significant gap in understanding these crucial aspects of coatings. This scarcity underscores the importance of investigating these topics, as they are pivotal in elucidating the complex dynamics of coatings. By delving into these areas, this research endeavors to enrich the existing knowledge base and provide valuable insights for future studies in the field. In this study, we investigate the impact of different coating time on the adhesion strength and tribological performance of TiCoCr PVD alloy treated with a novel duplex approach. By varying the coating time during the PVD process, the study aim to understand its effect on the surface morphology, composition, hardness, wear performance and corrosion resistance of TiCoCr PVD alloy. The study seeks to determine the optimal coating time to achieve the best adhesion strength and tribological performance of the coated alloy which is to be used in biomedical implants.

Author Contribution Statement

G. Godwin - Literature preparation and Methodology framework
M. Shunmuga Priyan - Paper Writing and Paper framework

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