CORROSION SCIENCE AND TECHNOLOGY, Vol.25, No.4(2026), pp.265~279 pISSN 1598-6462 / eISSN 2288-6524
[Review Paper] DOI: https://doi.org/10.14773/cst.2026.25.4.265

Advancements in Composite Systems Coatings by Electrophoretic Deposition on Biomedical Titanium Alloys: A Comprehensive Review on Properties and Corrosion Behaviors

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(Received May 23, 2025; Revised August 09, 2025; Accepted August 12, 2025)

Titanium (Ti) and its alloys are extensively used in biomedical applications due to their excellent mechanical properties, biocompatibility, and corrosion resistance. However, their bioinert surfaces can limit direct osseointegration and long-term clinical performance. To address these challenges, the development of nano-biocomposite coatings has emerged as a promising strategy to enhance the biological and functional properties of Ti-based implants. Electrophoretic deposition (EPD) is a straightforward, cost-effective, and versatile method for creating uniform and adherent coatings at room temperature. In this study, nano-biocomposite coatings of bioactive ceramics, such as hydroxyapatite, were applied to Ti alloy substrates, incorporating reinforcing metal or metal oxide nanoparticles like TiO_2, ZnO, or Ag via EPD. This review outlines the properties of Ti alloys and their most prevalent biomedical applications, as well as the EPD technique and the variables involved in coating Ti alloy surfaces. The coatings were characterized for morphology, adhesion strength, phase composition, and in vitro biological performance. The results demonstrated that EPD nano-biocomposite coatings significantly enhanced surface roughness, bioactivity, and antibacterial properties without compromising corrosion resistance. This study highlights the substantial potential of EPD-based nano-biocomposite coatings on Ti alloys for advanced medical implants, offering improved biological integration and clinical performance.

Keywords: *Electrophoretic deposition, Titanium alloys, Multi-composite coatings, Biocorrosion, Bioactivity*

1. Introduction

In recent times, biomaterials have evolved in placing their spotlight on medical applications. It is because of their need to be categorized as alternative materials for any body part to avoid losing its function, as well as their potential for full development into hip, knee, and heart replacements. The foremost concern for biomaterials has been to gain acceptance from the human body, followed by sufficient mechanical strength, good wear resistance, and excellent corrosion resistance in the highly corrosive environment generated by the human body [1-4]. Materials for biomedical applications should possess optimal levels of strength and toughness while being chemically stable and biocompatible [5]. Metallic biomaterials are the most commonly used types in orthopedic implants and dental devices due to their ability to modify properties and surfaces [6,7]. Today, significant metals and their alloys used in biomedical applications include stainless steel, Co-Cr alloys, commercially pure titanium (CP Ti) and its alloy, and magnesium alloys [2,3,8,9]. A comparison of the mechanical properties between these metallic biomaterials and cortical bone is illustrated in Table 1.

Titanium and its alloys are widely recognized for their exceptional combination of mechanical properties, corrosion resistance, and biocompatibility, making them indispensable in critical industries such as aerospace, biomedical, and marine engineering [15-18]. However, despite their advantageous bulk properties, titanium alloys suffer from limitations regarding surface performance. Their relatively low wear resistance, bioinertness, and vulnerability to corrosion in certain aggressive environments restrict their functional longevity in demanding applications [13,19,20]. To overcome these challenges, surface modification techniques have become a central focus of research, aiming to tailor the surface characteristics without compromising the core properties

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Table 1. Metallic biomaterials and their properties

Materials	Elastic Modulus (GPa)	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Fracture Toughness (MPa $\sqrt{m}$)	Elongation %	Ref.
316L Stainless Steel	200	200 - 700	500 - 1350	100	10 - 40	[2,10]
CoCrMo alloy	200 - 230	500 - 1500	900 - 1800	100	10 - 30	[10,11]
CP Ti & Ti alloys	55 - 110	170 - 1060	240 - 1100	80	6 - 25	[10,12]
Mg alloys	44	148 - 200	240 - 385	15 - 40	7 - 15	[10,13]
Cortical bone	10 - 30	100 - 120	130 - 150	6 - 12	3	[10,14]

of the base material. Among the various coating and surface engineering methods, Electrophoretic Deposition (EPD) has emerged as a particularly attractive approach due to its simplicity, low cost, and ability to deposit uniform and adherent coatings on complex-shaped components [21,22].

EPD is essentially a colloidal process that involves the migration of charged particles through a suspension medium and the subsequent deposition of those particles, all onto a conductive substrate when an electric field is applied. It is especially versatile, allowing for the deposition of a wide range of materials, including ceramics, polymers, metals, and nanomaterials. This method is highly promising for developing multi-composite coatings, where two or more phases are combined to impart multifunctional properties, including but not limited to corrosion resistance, mechanical strength, and enhanced biological performance [20-23].

The application of multi-composite coatings on titanium alloys through EPD is truly a remarkable opportunity for improving Titanium's behavior in various working environments. Such composite systems typically combine bioactive wear or corrosion-resistant phases to counterbalance the weaknesses of pure titanium surfaces. For example, combinations of hydroxyapatite (HA) with polymers and carbon-based nanomaterials, such as graphene, can yield coatings that are both bioactive and mechanically strong, as well as electrically conductive. This review aims to provide a comprehensive overview of the current state-of-the-art in the electrophoretic deposition of multi-composite coatings on titanium alloys. It discusses the fundamental principles of the EPD process, explores various material combinations and their benefits, outlines characterization methods, evaluates the improvements in performance metrics, and effects on corrosion behaviour. Moreover, it highlights existing challenges and future directions, setting a pathway for further innovation in this promising field.

2. Titanium and Its Alloys in the Biomedical Field

Titanium and its alloys are widely used in biomedical applications due to their excellent strength-to-weight ratio, corrosion resistance, biocompatibility, and low Young's modulus, which closely matches the cortical part of the replaced bone compared to other metallic biomaterials [24-26]. Table 2 presents the mechanical properties and corrosion potential of CP-Ti and various Ti alloys in different solutions, compared to cortical bone.

CP-Ti is suitable for non-load-bearing biomedical applications due to its exceptional biocompatibility, high ductility, and moderate strength [8]. Although Ti-6Al-4V is quite strong and resistant to fatigue, vanadium may cause issues with biocompatibility. For the reason that niobium is used instead of vanadium, Ti-6Al-7Nb has improved biocompatibility and comparable strength to Ti-6Al-4V, making it a perfect material for long-term implants [7,31]. Ti-13Nb-13Zr is an alloy designed for biomedical implants, especially in orthopedics. It offers a unique combination of high strength, good ductility, and a low elastic modulus —closer to natural bone—which helps reduce stress shielding. In contrast to Ti-6Al-4V, it is non-toxic and resistant to corrosion in bodily fluids since it includes biocompatible elements like zirconium and niobium. It is perfect for load-bearing implants, including dental implants, spinal devices, and hip and knee [32,33]. These properties support their application in orthopedic and dental implants, as well as other biomedical applications, as shown in Fig. 1 [7,23].

From a biochemical perspective, titanium alloys are

Table 2. Properties of selected titanium and its alloys compared to properties of human bone application in the biomedical field

Material	Elastic modulus (GPa)	Yield strength (MPa)	Tensile strength (MPa)	Corrosion potential (V)	The influence of elements on the human body	Ref.
CP-Ti (Grade 1–4)	105	170 - 485	240 - 550	-0.3 to 0.2 in 3.5%NaCl solution and Ag/AgCl reference electrode		[2,20,27]
Ti-6Al-4V	112	850 - 900	895 - 930	-0.4 in 3.5%NaCl solution and saturated calomel electrode (SCE)	V and Al are toxic and can cause Alzheimer's disease, osteomalacia, or neuropathy.	[20,28]
Ti-6Al-7Nb	114	880 - 950	900 - 1050	0.3 in Hank's solution and a saturated calomel electrode (SCE)	Al is toxic, Nb promotes apatite formation.	[2,20,29]
Ti-13Nb-13Zr	79 - 84	836 - 908	973 - 1037	0.2 in Ringer's solution and a saturated calomel electrode (SCE)	Nb promotes apatite formation.	[12,20,30]
Bone	10 - 30	100 - 120	130 - 150			[14]

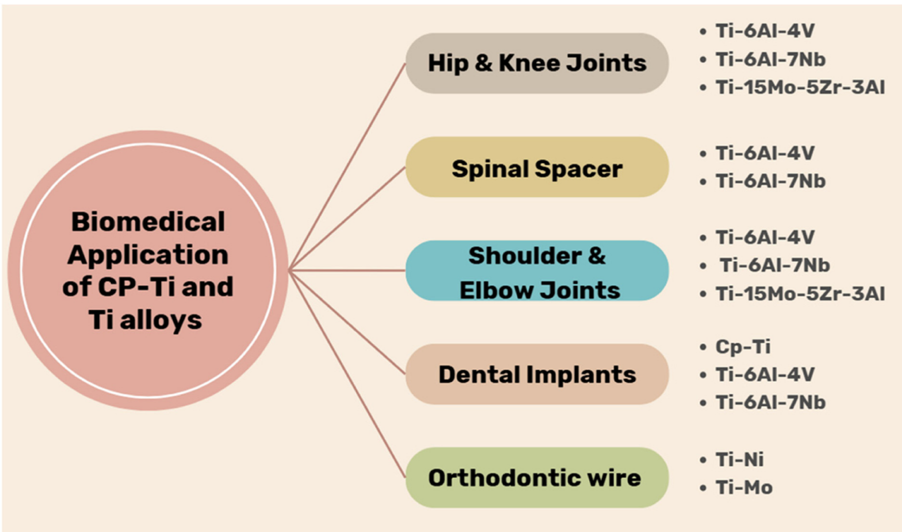

Fig. 1. Biomedical application of Ti and its alloys

considered nearly inert materials because they do not chemically or biologically bond with tissues upon implantation; rather, they are surrounded or even encapsulated by them [8,34].

Despite the excellent properties of titanium materials, concerns remain about their long-term stability and corrosion resistance in body fluid environments. The release of corrosion products can cause metal degradation, which may lead to implant loosening or deterioration of its properties. Additionally, some prostheses are rejected early after surgery due to allergic reactions. Furthermore, the implant must have an appropriate microstructure that promotes the formation of a permanent bond at the tissue-implant interface [16,22,25,35].

Based on the above, techniques for modifying the surface of metallic implants are being explored to meet these criteria, especially over the long term. Surface treatment is a common method to improve the bioactivity and anti-corrosion properties of titanium alloys using bioactive inorganic materials or bioactive glasses [18,25,35].

Another significant issue that may arise from using metallic implants, such as titanium-based implants, is the risk of bacterial infection. The surfaces of implants can develop biofilms that are highly resistant to standard antibiotics. Misuse of antibiotics can lead to a loss of microbial flora and adverse reactions [35-37]. Therefore, it is essential to create implant surfaces with enhanced resistance to bacterial contamination to prevent biofilm formation. A promising approach to developing biologically inspired surfaces for titanium biomaterials involves surface treatments, such as applying advanced coatings that improve both bioactivity and antibacterial properties.

The exceptional mechanical properties of the metallic substrate can be combined with the coatings' ability to promote bone formation and their antibacterial features. It is widely acknowledged that the ability of bioactive coatings to induce bone formation can enhance implant stability by improving cell adhesion and facilitating osseointegration [36,38].

3. Coatings in Biomedical Applications.

Coatings are essential for improving the performance, functionality, and biocompatibility of biomedical devices and implants. In the field of biomedical engineering, surface modification through coatings is crucial for enhancing corrosion resistance, wear resistance, bioactivity, and overall integration with biological tissues. Various techniques can be applied to modify metallic implants, including sol-gel, electrophoretic deposition (EPD), magnetic sputtering, plasma spraying, pulsed laser deposition, physical vapor deposition, chemical vapor deposition, Anodic oxidation, and electrodeposition, as shown in Fig. 2 [7,20,25,39].

EPD is often the preferred technique due to its simple setup and ability to produce uniform coatings, even on complex surface geometries [21,22]. Additionally, it facilitates coating application on materials with different forms, morphologies, roughness, crystallinity, chemical composition, wettability, corrosion resistance, and mechanical properties [20]. It is faster than sol-gel techniques. Moreover, EPD is a cost-effective electrochemical process that can be performed at room temperature. By adjusting the deposition parameters, the coating thickness and shape can be precisely controlled, unlike chemical vapor deposition (CVD) and physical vapor deposition (PVD), which require costly and complex equipment. Also, high temperatures are often necessary for CVD, which may not be appropriate for all materials [6]. Because the required tooling is inexpensive, manufacturing inputs and product dissemination may rise [6,20].

Fig. 2. Surface modification methods for Ti and Ti alloys in biomedical applications [40]

Table 3. Classification of coatings based on their material composition and biological function

Classification	Purpose	Materials	Applications	Ref.
Bioinert Coatings	Passive barrier, mechanical protection.	TiN, ZrO_2, Al_2O_3, and TiO_2.	Orthopedic implants, dental implants, and surgical tools.	[38]
Bioactive Coatings	Promote osseointegration and bone bonding.	HA, Bioglass, and Calcium phosphates.	Bone implants, dental implants.	[41]
Biodegradable Coatings	Controlled degradation, drug release.	PLA, PGA, Mg alloys, and Chitosan.	Resorbable stents, temporary scaffolds.	[42]
Antimicrobial Coatings	Prevent infection, resist biofilm formation.	Ag nanoparticles, ZnO, and Chitosan.	Catheters, implants, wound dressings.	[25]
Composite Coatings	Combine bioactivity, antimicrobial effect, and mechanical strength.	HA–Chitosan, TiO_2–Ag, and polymer–ceramic nanocomposites.	Advanced implants, multifunctional devices.	[43]

Biomedical coatings can be broadly categorized based on their biological function, material composition, or mechanism of action, as shown in Table 3.

4. Fundamentals of Electrophoretic Deposition.

Electrophoretic deposition (EPD) is a specialized colloidal processing technique that utilizes the electrophoresis mechanism to move charged particles suspended in a solution under an electric field, allowing for their ordered deposition on a substrate to create thin and thick films, coatings, and free-standing bodies [21,22]. The interest in EPD stems not only from its high versatility with various materials and material combinations but also from its cost-effectiveness, as it typically requires simple processing equipment and infrastructure. Additionally, EPD has significant potential for scaling up to large product sizes, ranging from micrometers to meters, and can be adapted for a variety of devices and component shapes [21,44,45]. EPD is typically conducted in a two-electrode cell, as illustrated schematically in Fig. 3. The movement of charged particles suspended in a liquid toward the working electrode is facilitated by electrophoresis, while the formation and growth of a solid deposit on the electrode largely result from particle coagulation [21,46,47]. EPD can be applied to a wide range of materials available in the form of fine powders (generally less than approximately 30 mm in particle size) or as colloidal suspensions. Metals, polymers, ceramics, glasses, and their composites can be deposited using EPD [21,48,49].

Over the past 25 years, interest in EPD has grown significantly, both in academia and the industrial sector. Numerous new applications for EPD in developing bulk materials and coatings are being reported [22]. There is also increasing interest in leveraging the advantages of EPD for nanomaterials and biological materials [50,51]. The application of EPD in the biomaterials field likely began with the development of hydroxyapatite (HA) $Ca_{10}(PO_4)_6(OH)_2$ coatings on Ti substrates in 1986 by Ducheyne, P. *et. al*. [52], gaining further attention with the work of Zhitomirsky & Gal-Or [53], which has also prompted investigations into the EPD of HA nanoparticles.

The need to develop multifunctional coatings that

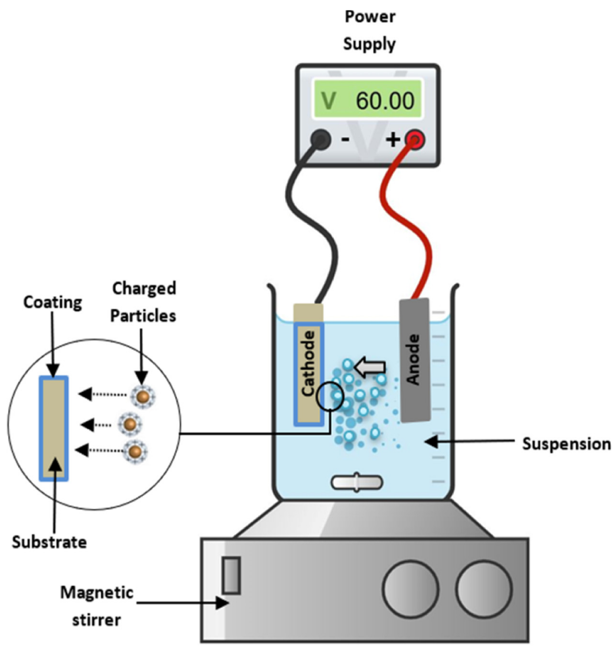

Fig. 3. Electrophoretic deposition (EPD) cell [21]

exhibit strong bonding ability to bone tissue, along with anti-infectious and antiallergic properties, has provided renewed impetus for EPD as the preferred technique for creating nanocomposite coatings [21]. Roether *et al*. [54], were the first to apply EPD to coat three-dimensional porous biodegradable polymer substrates with Bioglass particles for bone tissue engineering. Additionally, EPD has been demonstrated to fabricate composite biomaterials similar to the hydroxyapatite (HA)-reinforced polyethylene (PE) composite (HAPEX) [55]. The use of EPD in the biomedical sector is expanding to encompass a range of applications, including functional, nanostructured composite coatings, layered biomaterials, thin films, porous biomaterials, tissue scaffolds, drug delivery systems, and biosensors [21,56]. EPD, in conjunction with other electrochemical deposition methods, can serve as a preferred technique for developing advanced biomaterial structures. EPD is regarded as one of the electric field-assisted deposition methods that is gaining traction in the biomaterials field. The EPD technique can produce a wide range of coating thicknesses, as compared to other techniques in orthopedic applications, as illustrated in Fig. 4 [21].

4.1 Factors Affecting EPD

The mechanism of EPD involves charged particles in

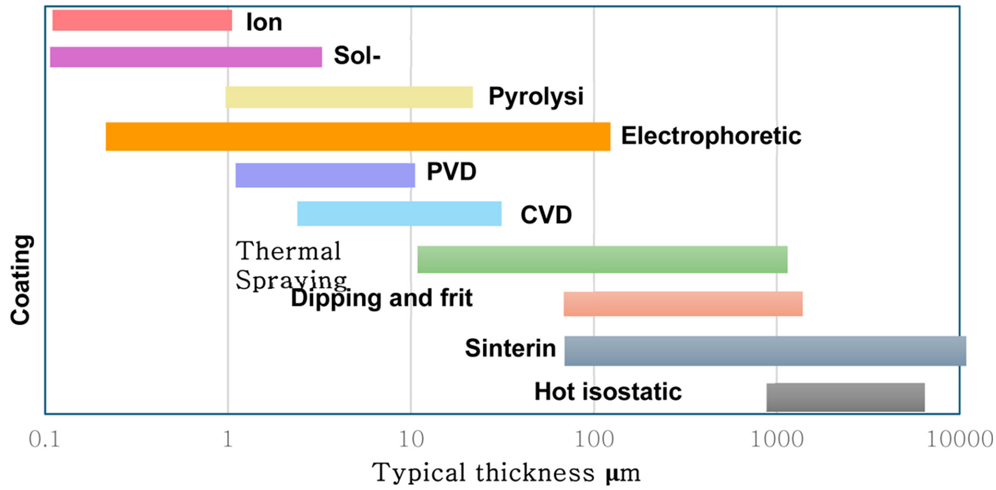

Fig. 4. Typical thickness of coatings obtained by different process methods for orthopedic applications

a suspension being deposited onto an electrode under the influence of an applied electric field. Two sets of parameters can affect both the EPD process and the resulting specimen: first, those that regulate the suspension's condition and quality, and second, those that govern the entire procedure, including the electrical settings. The latter can be modified to achieve advantageous deposition once the first group is established [21,22,57].

4.1.1 Parameters Associated with Suspension

The efficiency, quality, and reproducibility of the EPD process largely depend on the parameters of the suspension used, as shown in Fig. 5 [22,57]. Suspension stability is an important factor in electrophoretic deposition. A stable suspension provides homogeneous particle distribution and uniform coating quality. The stability of the suspension relies on the zeta potential, pH, ionic strength, and addition of dispersants or surfactants. The zeta potential, as a measure of electrostatic repulsion between the particles, should be high enough (positive or negative) to avoid agglomeration. Generally, values of more than ±30 mV are regarded as stable [23]. Some common dispersing agents are polyacrylic acid, polyethyleneimine, and ammonium polyacrylate. These are selected based on the surface chemistry of particles and the solvent type. Organic solvents such as ethanol and isopropanol are utilized in EPD because of their low conductivity and volatility, which reduce bubble generation and provide coating homogeneity. Sonication

Fig. 5. EPD Suspension Parameters

is also being widely utilized for de-agglomerating particles and achieving a homogeneous dispersion [57].

The suspension particle size has a strong influence on the electrophoretic powder deposition process, generating a deposition gradient. The deposited layer homogeneity is directly reliant on particle distribution and stability [21,23]. The dielectric constant needed for EPD relies on fluid properties; low constants discourage dissociation and electrophoresis. The double-layer region may be reduced by high ion concentrations, influencing conductivity. The suspension preparation method also influences conductivity. The ideal suspension possesses low conductivity, viscosity, and a high dielectric constant [21,23]. The zeta potential in EPD controls particle density, orientation, and velocity, which affects stability. Maintaining a strong surface charge is critical to prevent particle agglomeration and the formation of dense deposits [21,57]. Stable suspensions prevent agglomeration and sedimentation, while excessive stability disrupts the EPD process [22,57]. Low concentrations of suspended solids result in deposition rates based on each particle's electrophoretic mobility, while high concentrations ensure uniform and consistent deposition rates [57,58].

4.1.2 Parameters Related to the Process

The electric field, which drives electrophoresis, is compromised when free ions carry a portion of the driving force, which is the driving force of EPD. However, when free ions cannot be limited, the current carried by them is insignificant. The applied electric field should be entirely spent on electrophoresis advancement in a stable current manner, as deposition increases with applied potential. Moderate applied fields are suggested for the best deposit quality. High electric fields can cause turbulence in the suspension, compromising deposit quality and hindering the formation of a dense close-packed structure [21,22,57]. The deposition rate in EPD is linear with time, decreasing until the deposit thickens enough to disrupt conductance, reaching a plateau at high deposition times [57,59]. The quality of the deposited film in EPD is significantly influenced by the substrate's conductivity, with low conductivity causing slow deposition and nonuniformity [22,60].

5. Composite Coatings for Titanium Alloys

EPD facilitates the deposition of various composite coatings, which can be classified into the following categories, as shown in Table 4:

Many studies recommend biocompatible coatings on the metallic substrate. Coating with Bioactive materials, including hydroxyapatite (HA) [$Ca_{10}(PO_4)_6(OH)_2$], and bioactive glass to reduce direct metal-body fluid interaction and restrict the discharge of undesirable metallic ions into the body. Coating Ti implants with HA has been shown to improve their fixation capabilities in several in vivo investigations. Also, the chemical composition, structural, and biological properties of HA are close to those of bone tissue [18,38,66].

Researchers focus on a wide range of research concerning composite coatings used for surface modification of Ti alloys through EPD across various parameters, specifically relating to biomedical applications. The preparation process of this article is based on several fundamentals: subject matter (titanium and its alloys, electrophoretic deposition), publication date (generally within the last 15 years), and composite coatings (the influence of process parameters on the properties of coatings).

5.1 Effect of Composite Coating on Characteristics of the Ti Alloy Implants

Recent advancements in surface modification of titanium and its alloys have highlighted the potential of EPD techniques for biomedical applications. Julia Flesinska *et al*. [6] investigated porous titanium biomaterials modified via EPD with chitosan coatings, revealing that ethanol content directly influences coating

Table 4. Composite coating materials by using EPD and their functions

Composite Coatings	Types	Functions	Ref.
Ceramic-Based Coatings	Hydroxyapatite (HA), zirconia, and alumina-based coatings.	Enhance the biocompatibility and wear resistance of titanium implants.	[18,61,62]
Polymer-Based Coatings	Chitosan, polylactic acid (PLA), and polyethylene glycol (PEG) coatings.	Improve bioactivity and provide drug-loading capabilities.	[24,36,63]
Metal-Based Coatings	Silver, copper, and platinum-based coatings.	Impart antibacterial and corrosion-resistant properties.	[25,35]
Carbon-Based Coatings	Carbon nanotube.	Improve mechanical strength, electrical conductivity, and tribological properties.	[64,65]

morphology and thickness, with optimal parameters (10 V for 30 minutes) yielding uniform, non-cytotoxic coatings with excellent cell viability. Similarly, Gaafar *et al*. [43] enhanced the stability and uniformity of hydroxyapatite/chitosan (HA/CS) coatings on titanium using dispersing agents such as polyvinyl butyral (PVB), polyethylene glycol (PEG), and triethanolamine (TEA), achieving significant corrosion resistance improvements. Pawłowski *et al*. [63] examined chitosan/Eudragit E 100 coatings on titanium Grade 2, demonstrating superior mechanical properties and corrosion resistance when deposited at 10 V for 1 minute with 0.25 g of Eudragit. Abed, Areege K *et al*. [67] a layer-by-layer coating was produced using electrophoretic deposition for an HA/ Al_2O_3 coating layer and a bioglass coating layer on Co-Cr-Mo alloy with a roughness of 0.5 μm (400 emery paper SiC). The corrosion behaviour was analyzed by assessing the coating layers' exceptional corrosion resistance. Aydın *et al.* [61] optimized HA coatings on Ti6Al7Nb alloys, concluding that 100 V for 1 minute provided the most crack-free and mechanically favorable coatings. Fiołek *et al*. [68], successfully co-deposited Si_3N_4 /PEEK 708 nanocomposites on Ti-6Al-4V with chitosan as a dispersant, achieving strong adhesion, good tribological properties, and controlled crystallinity via post-heat treatments. Yin *et al*. [62], introduced yttria-stabilized zirconia (YSZ) coatings on CP-Ti implants, demonstrating improved bioactivity, cellular compatibility, and inflammatory response suppression. Moskalewicz *et al.* [18], created crack-free nanocomposite HA/chitosan coatings on Ti6Al7Nb via EPD, showing optimal adhesion at 10 V for 240 seconds from a 4 g/L HA suspension. Seuss *et al*. [69], developed bioactive glass/ chitosan coatings using AC-EPD, revealing that BG particle size influenced hydroxyapatite formation and antibacterial efficacy after 21 days in SBF. In another study, Moskalewicz *et al*. [24], fabricated microporous PEEK/Bioglass® coatings on Ti–6Al–7Nb alloys, optimizing deposition parameters and adhesion via post-deposition heat treatment. Erakovic *et al*. [25], modified HA coatings with lignin and silver to enhance corrosion resistance and antibacterial properties, demonstrating favorable surface porosity and bioactivity in SBF. Mohan *et al*. [38], applied nano-TiO_2/HA coatings via EPD on Ti–13Nb–13Zr, showing that sintered coatings had improved adhesion and corrosion resistance, although unsintered samples had less interconnected porosity. Balamurugan *et al*. [70], developed functionally graded Bioglass–apatite coatings on Ti6Al4V, finding significant shifts in corrosion potential and improved electrochemical behavior in SBF. Guo *et al.* [71], used a two-step method to produce HA/Fe_3O_4 coatings with macro- and mesoporous structures on Ti6Al4V, enhancing in vitro bioactivity. Finally, Wang *et al.* [72], demonstrated the superiority of Co–YSZ/HA nanocomposite coatings over HA-only coatings, thanks to improved mechanical properties and adhesion through a Co–YSZ interlayer.

5.2 Influence of Composite Coatings on Corrosion Behavior of the Ti Alloy Implants

The main function of composite coatings in corrosion protection is to serve as an effective barrier between the titanium substrate and the external environment. In vivo, titanium alloys are constantly subjected to a dynamic environment rich in electrolytes, proteins, and varying pH levels. Although Ti naturally forms a passive oxide layer (primarily TiO_2), this film can be damaged over time, leading to pitting, crevice corrosion, and ion leaching (such as Al or V ions from Ti-6Al-4V). These degradation processes can be worsened by mechanical wear or bacterial colonization, especially in load-bearing implants or during inflammation. Several studies have shown that such coatings markedly reduce corrosion current density (I_corr), increase corrosion potential (E_corr), and expand passivation ranges in simulated body fluid (SBF).

Table 5 shows the effect of composite coating on the corrosion behaviour of Ti and its alloy substrate. Erakovic *et al.* [25], discovered that silver/hydroxyapatite (Ag/ HAP) and silver/hydroxyapatite/lignin (Ag/HAP/Lig) coatings enhance the corrosion resistance and bioactivity of titanium implants. Silver offers antimicrobial properties, while lignin boosts mechanical stability. Both coatings maintained good corrosion resistance, but Ag/HAP/Lig showed superior corrosion behavior due to its uniform surface, better wettability, and structural stability. The addition of lignin preserves the structural integrity of HAP, making it a promising material for biomedical implants. Gaafar *et al.* [43], achieved a significant improvement in corrosion resistance when titanium was coated with hydroxyapatite/chitosan nanocomposites using dispersants such as Polyvinyl butyral (PVB), Polyethylene glycol (PEG), and Triethanolamine (TEA). This resulted in reduced corrosion current density and increased polarization resistance, with PVB-coated samples performing best. PVB and PEG produced denser, more uniform coatings with fewer defects, enhancing barrier properties. Łukasz *et al*. [63], compared titanium implants coated with chitosan and chitosan/Eudragit E 100 (chit/EE100) in artificial saliva at 37 ºC. Both coatings significantly improved corrosion resistance, with chitosan demonstrating superior performance by lowering corrosion current density. Mohan *et al.* [38], improved the corrosion resistance of Ti-13Nb-13Zr alloys by coating them with a hydroxyapatite/titanium dioxide nanocomposite. The coating greatly enhanced corrosion resistance, lowering current density and promoting passivation. Its dense structure reduced porosity and metal ion release. Additionally, Tomasz *et al*. [36], reduced the corrosion current density from 20 µA/cm^2 to 1 µA/cm^2 by using multicomponent coatings of sodium alginate, hydroxyapatite, and graphite oxide (GtO/HA/SA) on a Ti-13Nb-13Zr alloy, compared to the hydroxyapatite/titanium dioxide nanocomposite used by Mohan *et al.* [38]. The coating's high polarization resistance and capacitive behavior indicate a strong barrier effect. This coating has the potential to improve implant stability and biocompatibility in physiological environments. Kalis *et al*. [73], used a thin film of Nb_2O_5 or a monolayer of graphene coated on Ti6Al4V. The Nb_2O_5 coating significantly improved corrosion resistance under harsh dental conditions due to its enhanced barrier properties and mechanical toughness. Graphene-coated Ti6Al4V exhibited the best corrosion protection because of its low current density and favorable corrosion potential. The study suggests that an Nb_2O_5/graphene hybrid system could enhance corrosion resistance in future biomedical applications. Elzbieta *et al.* [65], reveal that multiwalled carbon nanotubes (CNTs) coated titanium samples show higher open circuit potential and a positive shift in corrosion potential compared to unmodified titanium. The

Table 5. Effect of composite coating types on corrosion current density of Ti and Ti alloys

Composite coating type	Substrate	Electrolyte solution	Corrosion Current Density	Corrosion Resistance	Ref.
Silver/hydroxyapatite (Ag/HAP) Silver/hydroxyapatite/lignin (Ag/HAP/Lig)	Ti substrate	Kokubo's simulated body fluid.	-	Enhance corrosion stability and improve bioactivity.	[25]
Hydroxyapatite-chitosan with: Polyvinyl butyral (PVB) Polyethylene glycol (PEG) Triethanolamine (TEA).	Ti substrate	Ringer electrolyte solution.	0.0873 mA/cm^2 uncoated. 0.0153 mA/cm^2 with PVB. 0.0187 mA/cm^2 with PEG. 0.0296 mA/cm^2 with TEA.	High corrosion resistance of the Ti substrate coated with the HA/CS composite and dispersants.	[43]
Chitosan Chitosan/Eudragit E100	Ti grade 2 substrate	Artificial saliva solution at 37 ºC	794.15 nA/cm^2 for uncoated. 4.79 nA/cm^2 for chitosan. 93.79 nA/cm^2 for chit/EE100.	Chit/EE100 has slightly lower corrosion resistance compared to the chitosan coating.	[63]
TiO2 + 50%HAp nanoceramic	Ti-13Nb-13Zr	Simulated Body Fluid (SBF-Hank's solution).	3.442×10^{-5} mA/cm^2 for uncoated 1.864 × 10^{-6} mA/cm^2	TiO_2 + 50%HAp improve the corrosion Resistance.	[38]
Niobium oxide (Nb_2O_5) Graphene	Ti-Al-V	0.5M/l NaCl, 2g/L KF, pH=2 adjusted by concentrated hydrochloric acid.	60.50 µA/cm^2 for uncoated. 0.24 µA/cm^2 for Nb_2O_5. 0.01 µA/cm^2 for graphene.	Nb_2O_5 & Graphene enhance the corrosion resistance.	[73]
Graphite oxide /Hydroxyapatite / Sodium alginate (GtO/HA/SA).	Ti-13Nb-13Zr	Ringer's solution.	20µA/cm^2 uncoated alloy. 24µA/cm^2 for HA/SA. 1 µA/cm^2 for GtO/HA/SA.	Graphite oxide improved the corrosion resistance.	[36]
Multiwalled carbon nanotubes (CNTs).	Ti	Ringer's solution.	20 × 10^{-8} A/cm^2 for uncoated. 112 × 10^{-8} A/cm^2 for CNT.	CNT-coated titanium is more prone to corrosion than unmodified titanium.	[65]

CNT layer integrates with the TiO_2 oxide layer, forming a nanocomposite interface. This increases corrosion current due to electrical conductivity, not material loss. CNT coating improves biointegration and mechanical performance but lowers polarization resistance.

Composite coatings provide a multifaceted solution to enhance the corrosion resistance and biological performance of Ti alloys in biomedical applications. The synergistic effect of combining ceramics, polymers, and metal oxides has led to significant improvements in implant safety and functionality. Continued innovation in coating design and deposition techniques holds promise for the development of next-generation biomedical implants with superior performance.

5.3 Coating–Substrate Interface and Adhesion Mechanisms

Strong interfacial adhesion is essential for the long-term success of EPD coatings, especially in biomedical implants exposed to mechanical stresses and fluids. However, many EPD studies mainly focus on surface morphology and bioactivity, providing limited information about coating adhesion strength or failure modes. Poor interfacial bonding can lead to delamination, which compromises implant function and biocompatibility. Moskalewicz *et al.* [18], demonstrated that deposition time and voltage significantly impact the adhesion strength of HA/CS coatings on Ti6Al7Nb, with post-heat treatments playing a key role in reducing internal stresses and enhancing mechanical interlocking. Likewise, adding adhesion-promoting interlayers such as titania (TiO_2) or niobium oxide (Nb_2O_5) has been shown to improve bonding through both mechanical anchoring and chemical affinity. Despite these positive developments, a systematic evaluation using standardized mechanical tests such as pull-off adhesion, nanoindentation, or interfacial fracture toughness analysis remains necessary.

5.4 Nanotoxicity and Biodegradation Challenges

Although the properties of nanomaterials, including silver, titanium dioxide, and carbon nanotubes, provide multiple beneficial functions to the EPD coatings, concerns about their biosafety have not been sufficiently studied in many reports. For instance, silver nanoparticles have been shown to possess great antimicrobial capabilities, however, they can also induce cytotoxicity or immune responses if they are emitted in high amounts. Also, carbon-based nanostructures, such as GO and CNTs, might evoke oxidative stress in recipient cells because of their large specific surface area and reactive functional groups [74]. However, there are limited existing works concerning the long-term degradation of polymer-based coatings as well as their byproducts in physiological media. Moreover, the absence of a thorough biological characterization, including in vivo toxicity, genotoxicity, and immunogenicity, has become a major obstacle in clinical transfer. Investigators should conform to the ISO 10993-1 standard for biocompatibility when conducting experiments and incorporate cytotoxicity, hemocompatibility, and histometric evaluation into coating performance analysis.

6. Performance Enhancement through EPD-Coated Titanium Alloys

Titanium alloys can be modified using EPD, which provides uniform and good adhesion coatings, bringing improved surface properties of Ti and its alloys. Such coatings range from bioactive ceramics to polymers and composites, and have a wide range of applications, including corrosion and wear protection, biomedical, and aerospace. The EPD method also offers more precise control over the thickness and morphology of the coating, which could be tailored to provide different surface features but to keep the bulk properties of the substrate (titanium). These coatings facilitate bio-medical implants (hydroxyapatite EPD coating) for better osseointegration without the risk of implant rejection, as reported, and also in aerospace components (ceramic or carbon EPD coating) for thermal barrier protection and long life under extreme conditions. In summary, the use of EPD-coated layers on titanium alloys can offer a flexible and cost-efficient means of improving service life, mechanical performance, and surface functionalities in a way that is carefully tuned to the end applications.

7. Challenges and Future Perspectives

Despite the many advantages of EPD, there are still some technical and practical issues that act as barriers to fully realizing its capabilities. One major challenge is achieving uniform deposition over complex geometries, because of the field gradients and particle mobility, which can cause the coating to be uneven. Additionally, ensuring good adhesion between the deposited layer and the substrate remains a significant problem, especially when dealing with different materials or non-conductive surfaces. Long-term reliability is also a concern, particularly in harsh environments where moisture, temperature changes, and mechanical stresses can affect their performance over time. Current research trends show increasing interest in new strategies to overcome these challenges. For example, creating nanostructured coatings with enhanced mechanical and functional properties is possible due to their high specific surface area and adaptable design. Multi-layered coating systems are being investigated to combine the strengths of different materials, improving protection and functionality. Moreover, hybrid approaches that integrate EPD with other surface modification techniques, such as sol-gel processing, plasma treatment, or anodization, are demonstrating potential to enhance adhesion, durability, and overall performance.

Looking ahead, future research should prioritize in-depth mechanistic studies to better understand particle-substrate interactions, the kinetics of deposition, and the role of suspension chemistry in determining final coating quality. Moreover, translating laboratory-scale advances into large-scale, cost-effective industrial processes remains a critical goal. Addressing issues such as scalability, process control, and compatibility with existing manufacturing lines will be essential for the widespread adoption of EPD technology in sectors such as biomedical devices, electronics, energy storage, and protective coatings.

8. Conclusion

This review highlights the significant progress and promising future of electrophoretic deposition (EPD) as a surface modification technique for enhancing the performance of titanium and its alloys in biomedical applications. Titanium-based implants, while mechanically robust and biocompatible, suffer from bioinert surfaces and susceptibility to localized corrosion, which may compromise long-term implant integration and functionality. EPD offers a versatile, cost-effective, and scalable approach for the deposition of uniform, adherent, and multifunctional composite coatings under mild conditions.

Through an in-depth survey of literature from the past two decades, it is evident that EPD has enabled the successful fabrication of diverse composite coatings—including ceramics (e.g., hydroxyapatite), polymers (e.g., chitosan), metals (e.g., silver, copper), and carbon-based nanomaterials (e.g., CNTs, GO)—each tailored to improve specific implant functions such as osseointegration, antibacterial activity, mechanical integrity, and corrosion resistance. Studies consistently report enhancements in corrosion potential, reduction in corrosion current density, and improved biological responses, confirming the value of EPD-modified surfaces.

However, the review also reveals ongoing challenges, such as ensuring long-term adhesion, achieving uniform coatings on complex geometries, and understanding the biological impacts of nanomaterial-based coatings, particularly concerning cytotoxicity and biodegradation. Furthermore, standardized evaluation of adhesion strength and mechanical robustness remains underdeveloped across many studies, limiting direct comparison and industrial translation. The Future research should therefore focus on:

· Developing standardized mechanical and biological evaluation protocols for EPD coatings.

· Integrating hybrid and multilayered deposition strategies to enhance coating functionality and durability.

· Advancing in vivo studies and toxicity assessments to ensure clinical safety.

· Addressing scale-up challenges and process control for large-scale biomedical manufacturing.

In conclusion, EPD stands at the forefront of surface engineering for titanium biomedical implants, offering unparalleled flexibility in materials design and deposition. With continued interdisciplinary research, EPD is poised to deliver next-generation implant surfaces that meet the demanding requirements of biocompatibility, longevity, and multifunctionality in clinical applications.

References

1. I. Hulka, N. R. Florido-Suarez, J. C. Mirza-Rosca, and A. Saceleanu, Mechanical Properties and Corrosion Behavior of Thermally Treated Ti-6Al-7Nb Dental Alloy,

Materials, **15**, 3813 (2022). Doi: https://doi.org/10.3390/ma15113813

2. W. Abd-Elaziem, M. A. Darwish, A. Hamada, and W. M. Daoush, Titanium-Based alloys and composites for orthopedic implants Applications: A comprehensive review, *Materials & Design*, **241**, 112850 (2024). Doi: https://doi.org/10.1016/j.matdes.2024.112850
3. H. Shi, P. Zhou, J. Li, C. Liu, and L. Wang, Functional Gradient Metallic Biomaterials: Techniques, Current Scenery, and Future Prospects in the Biomedical Field, *Frontiers in Bioengineering and Biotechnology*, **8**, 1 (2021). Doi: https://doi.org/10.3389/fbioe.2020.616845
4. M. Hussein, A. Mustafa, and M. Abdulkareem, Using Taguchi Design to Compare the Corrosion Behavior of Commercial Pure Ti Alloys Coated by Dip and Electrophoretic Deposition with YSZ, *Engineering and Technology Journal*, **41**, 1588 (2023). Doi: https://doi.org/10.30684/etj.2023.143016.1557
5. T. S. Pinheiro, J. Gallego, C. Bolfarini, C. S. Kiminami, A. M. Jorge, and W. J. Botta, Microstructural evolution of Ti-6Al-7Nb alloy during high pressure torsion, *Materials Research*, **15**, 792 (2012). Doi: https://doi.org/10.1590/S1516-14392012005000102
6. J. Flesińska, M. Szklarska, I. Matuła, A. Barylski, S. Golba, J. Zając, M. Gawlikowski, P. Kurtyka, B. Ilnicka, and G. Dercz, Electrophoretic Deposition of Chitosan Coatings on the Porous Titanium Substrate, *Journal of Functional Biomaterials*, **15**, 190 (2024). Doi: https://doi.org/10.3390/jfb15070190
7. M. Sarraf, E. Rezvani Ghomi, S. Alipour, S. Ramakrishna, and N. Liana Sukiman, A state-of-the-art review of the fabrication and characteristics of titanium and its alloys for biomedical applications, *Bio-Design and Manufacturing*, **5**, 371 (2022). Doi: https://doi.org/10.1007/s42242-021-00170-3
8. M. Geetha, A. K. Singh, R. Asokamani, and A. K. Gogia, Ti based biomaterials, the ultimate choice for orthopaedic implants - A review, *Progress in Materials Science*, **54**, 397 (2009). Doi: https://doi.org/10.1016/j.pmatsci.2008.06.004
9. S. A. Hussain, U. Rajak, and S. B. C, Multi Wear Response Optimization of Ti-6Al-7Nb Biomedical Alloy, *International Journal of Innovative Technology and Exploring Engineering*, **12**, 19 (2023). Doi: https://doi.org/10.35940/ijitee.b9409.0112223
10. Q. Chen and G. A. Thouas, Metallic implant biomaterials, *Materials Science and Engineering: R: Reports*, **87**, 1 (2015). Doi: https://doi.org/10.1016/j.mser.2014.10.001
11. K. Posiyano, R. V. S. Prasad, T. C. Dzogbewu, E. O. Olakanmi, T. P. Leso, K. Setswalo, and A. T. Sello, The potential of Ti-6Al-7Nb, and design for manufacturing considerations in mitigating failure of hip implants in service, *Biomedical Engineering Advances*, **8**, 100136 (2024). Doi: https://doi.org/10.1016/j.bea.2024.100136
12. M. Balazic and J. K. Machining, Medicine, Review: titanium and titanium alloy applications in, *Int. J. Nano and Biomaterials*, **1**, 3 (2007). Doi: https://doi.org/10.1504/IJNBM.2007.016517
13. R. Davis, A. Singh, M. J. Jackson, R. T. Coelho, D. Prakash, C. P. Charalambous, W. Ahmed, L. R. R. da Silva, and A. A. Lawrence, A comprehensive review on metallic implant biomaterials and their subtractive manufacturing, *The International Journal of Advanced Manufacturing Technology*, **120**, 1473 (2022). Doi: https://doi.org/10.1007/s00170-022-08770-8
14. Q. Chen and G. Thouas, Biomaterials: A Basic Introduction (1st ed.), CRC Rress (2014). Doi: https://doi.org/10.1201/b17553
15. Z. Mukhtar, A. Dey, and N. Kundan, Optimized surface engineering of Ti-6Al-4V: Comprehensive coating evaluation for biomedical applications, *Surfaces and Interfaces*, **56**, 105735 (2025). Doi: https://doi.org/10.1016/j.surfin.2024.105735
16. M. R. Siti Nur Hazwani, L. X. Lim, Z. Lockman, and H. Zuhailawati, Fabrication of titanium-based alloys with bioactive surface oxide layer as biomedical implants: Opportunity and challenges, *Transactions of Nonferrous Metals Society of China*, **32**, 1 (2022). Doi: https://doi.org/10.1016/S1003-6326(21)65776-X
17. M. Wollmann, J. Kiese, L. Wagner, *Proc. 12th World Conference on Titanium*, **2**, 837 (2012). https://cdn.ymaws.com/titanium.org/resource/resmgr/ZZ-WCTP2011-VOL2/2011_Vol.2-1-O2-Properties_a.pdf
18. T. Moskalewicz, M. Kot, S. Seuss, A. Kędzierska, A. Czyrska-Filemonowicz, and A. R. Boccaccini, Electrophoretic deposition and characterization of HA/chitosan nanocomposite coatings on Ti6Al7Nb alloy, *Metals and Materials International*, **21**, 96 (2015). Doi: https://doi.org/10.1007/s12540-015-1011-y
19. L. Shao, Y. Du, K. Dai, H. Wu, Q. Wang, J. Liu, Y. Tang, and L. Wang, β-Ti Alloys for Orthopedic and Dental Applications: A Review of Progress on Improvement of Properties through Surface Modification, *Coatings*, **11**, 1446 (2021). Doi: https://doi.org/10.3390/coatings11121446
20. B. Makurat-Kasprolewicz and A. Ossowska, Electropho-

retically deposited titanium and its alloys in biomedical engineering: Recent progress and remaining challenges, *Journal of Biomedical Materials Research Part B: Applied Biomaterials*, **112**, 1 (2024). Doi: https://doi.org/10.1002/jbm.b.35342
21. A. R. Boccaccini, S. Keim, R. Ma, Y. Li, and I. Zhitomirsky, Electrophoretic deposition of biomaterials, *Journal of The Royal Society Interface*, **7**, 581 (2010). Doi: https://doi.org/10.1098/rsif.2010.0156.focus
22. L. Besra and M. Liu, A review on fundamentals and applications of electrophoretic deposition (EPD), *Progress in Materials Science*, **52**, 1 (2007). Doi: https://doi.org/10.1016/j.pmatsci.2006.07.001
23. E. Marin and A. Lanzutti, Biomedical Applications of Titanium Alloys: A Comprehensive Review, *Materials*, **17**, 114 (2023). Doi: https://doi.org/10.3390/ma17010114
24. T. Moskalewicz, S. Seuss, and A. R. Boccaccini, Microstructure and properties of composite polyetheretherketone/ Bioglass® coatings deposited on Ti-6Al-7Nb alloy for medical applications, *Applied Surface Science*, **273**, 62 (2013). Doi: https://doi.org/10.1016/j.apsusc.2013.01.174
25. S. Eraković, A. Janković, D. Veljović, E. Palcevskis, M. Mitrić, T. Stevanović, D. Janaćković, and V. Miskovic-Stankovic, Corrosion stability and bioactivity in simulated body fluid of silver/hydroxyapatite and silver/hydroxyapatite/lignin coatings on titanium obtained by electrophoretic deposition, *Journal of Physical Chemistry B*, **117**, 1633 (2013). Doi: https://doi.org/10.1021/jp305252a
26. M. B. Hussein, A. M. Mustafa, and M. H. Abdulkareem, A Comparative Study on Dip Coating and Corrosion Behavior of Ti-13Zr-13Nb and Commercially Pure Titanium Alloys Coated with YSZ by Taguchi Design., *Salud, Ciencia y Tecnología - Serie de Conferencias*, **3**, 847 (2024). Doi: https://doi.org/10.56294/sctconf2024847
27. M. Nie, C. T. Wang, M. Qu, N. Gao, J. A. Wharton, and T. G. Langdon, The corrosion behaviour of commercial purity titanium processed by high-pressure torsion, *Journal of Materials Science*, **49**, 2824 (2014). Doi: https://doi.org/10.1007/s10853-013-7988-z
28. N. Dai, L. C. Zhang, J. Zhang, Q. Chen, and M. Wu, Corrosion behavior of selective laser melted Ti-6Al-4 V alloy in NaCl solution, *Corrosion Science*, **102**, 484 (2016). Doi: https://doi.org/10.1016/j.corsci.2015.10.041
29. S. L. De Assis, S. Wolynec, and I. Costa, Corrosion characterization of titanium alloys by electrochemical techniques, *Electrochimica Acta*, **51**, 1815 (2006). Doi: https://doi.org/10.1016/j.electacta.2005.02.121
30. I. Cvijović-Alagić, Z. Cvijović, S. Mitrović, V. Panić, and M. Rakin, Wear and corrosion behaviour of Ti-13Nb-13Zr and Ti-6Al-4V alloys in simulated physiological solution, *Corrosion Science*, **53**, 796 (2011). Doi: https://doi.org/10.1016/j.corsci.2010.11.014
31. M. Niinomi, Mechanical properties of biomedical titanium alloys, *Materials Science and Engineering A*, **A243**, 231 (1998). Doi: https://doi.org/10.1016/S0921-5093(97)00806-X
32. M. Niinomi and M. Nakai, Titanium-Based Biomaterials for Preventing Stress Shielding between Implant Devices and Bone, *International Journal of Biomaterials*, **2011**, 836587 (2011). Doi: https://doi.org/10.1155/2011/836587
33. M. Niinomi, Recent research and development in titanium alloys for biomedical applications and healthcare goods, *Science and Technology of Advanced Materials*, **4**, 445 (2003). Doi: https://doi.org/10.1016/j.stam.2003.09.002
34. Y. Kirmanidou, M. Sidira, M.-E. Drosou, V. Bennani, A. Bakopoulou, A. Tsouknidas, N. Michailidis, and K. Michalakis, New Ti-Alloys and Surface Modifications to Improve the Mechanical Properties and the Biological Response to Orthopedic and Dental Implants: A Review, *BioMed Research International*, **2016**, 2908570 (2016). Doi: https://doi.org/10.1155/2016/2908570
35. H. A. Hameed, H. A. Hasan, N. Luddin, A. Husein, A. Ariffin, and M. K. Alam, Osteoblastic Cell Responses of Copper Nanoparticle Coatings on Ti-6Al-7Nb Alloy Using Electrophoretic Deposition Method, *BioMed Research International*, **2022**, 3675703 (2022). Doi: https://doi.org/10.1155/2022/3675703
36. T. Moskalewicz, M. Warcaba, A. Łukaszczyk, M. Kot, A. Kopia, Z. Hadzhieva, and A. R. Boccaccini, Electrophoretic deposition, microstructure and properties of multicomponent sodium alginate-based coatings incorporated with graphite oxide and hydroxyapatite on titanium biomaterial substrates, *Applied Surface Science*, **575**, 151688 (2022). Doi: https://doi.org/10.1016/j.apsusc.2021.151688
37. H.-L. Huang, M.-T. Tsai, Y.-Y. Chang, Y.-J. Lin, and J.-T. Hsu, Fabrication of a Novel Ta(Zn)O Thin Film on Titanium by Magnetron Sputtering and Plasma Electrolytic Oxidation for Cell Biocompatibilities and Antibacterial Applications, *Metals*, **10**, 649 (2020). Doi: https://doi.org/10.3390/met10050649
38. L. Mohan, D. Durgalakshmi, M. Geetha, T. S. N. Sankara Narayanan, and R. Asokamani, Electrophoretic deposition of nanocomposite (HAp + TiO_2) on titanium

alloy for biomedical applications, *Ceramics International*, **38**, 3435 (2012). Doi: https://doi.org/10.1016/j.ceramint.2011.12.056

39. M. Sathish, N. Radhika, and B. Saleh, A critical review on functionally graded coatings: Methods, properties, and challenges, *Composites Part B: Engineering*, **225**, 109278 (2021). Doi: https://doi.org/10.1016/j.compositesb.2021.109278
40. X. Han, J. Ma, A. Tian, Y. Wang, Y. Li, B. Dong, X. Tong, and X. Ma, Surface modification techniques of titanium and titanium alloys for biomedical orthopaedics applications: A review, *Colloids and Surfaces B: Biointerfaces*, **227**, 113339 (2023). Doi: https://doi.org/10.1016/j.colsurfb.2023.113339
41. K. E. Öksüz, Bioactive coatings on biopolymer materials: evaluation of mechanical, physical, thermal, and in vitro properties, *Journal of the Australian Ceramic Society*, **60**, 1265 (2024). Doi: https://doi.org/10.1007/s41779-024-01037-3
42. M. Mohammadi-Zerankeshi, M. Zohrevand, and R. Alizadeh, Hydrothermal Coating of the Biodegradable Mg-2Ag Alloy, *Metals*, **13**, 1260 (2023). Doi: https://doi.org/10.3390/met13071260
43. M. S. Gaafar, S. M. Yakout, Y. F. Barakat, and W. Sharmoukh, Electrophoretic deposition of hydroxyapatite/chitosan nanocomposites: the effect of dispersing agents on the coating properties, *RSC Advances*, **12**, 27564 (2022). Doi: https://doi.org/10.1039/d2ra03622c
44. R. Rawdan, M. Abdulkareem, and A. Mustafa, Optimizing of Coating Layers Parameters of (Nano Hydroxyapatite/TiO_2 NPs) on Nitinol SMAs by Electrophoretic Deposition, *Engineering and Technology Journal*, **38**, 530 (2020). Doi: https://doi.org/10.30684/etj.v38i4A.577
45. A. A. Abdulhasan, E. L. Sheng, A. M. Mustafa, and M. R. Bin Isa, Recent Advancements in Biocompatible Coatings for Metallic and Non-Metallic Biomaterials: A Review, *Corrosion Science and Technology*, **23**, 449 (2024). Doi: https://doi.org/10.14773/cst.2024.23.5.449
46. S. N. Heavens, Electrophoretic deposition as a processing route for ceramics., *In Advanced ceramic processing and technology, Noyes Publications*, p. 255, Park Ridge, NJ (1990).
47. P. & N. Sarkar, Electrophoretic deposition (EPD): mechanism, kinetics and application to ceramics, *Journal of the American Ceramic Society*, **79**, 1987 (1996). Doi: https://doi.org/10.1111/j.1151-2916.1996.tb08929.x
48. M. S. J. Gani, Electrophoretic deposition-A review, *Industrial Ceramics*, **14**, 163 (1994).
49. O. O. van der Biest and L. J. Vandeperre, Electrophoretic deposition of materials, *Annual Review of Materials Research*, **29**, 327 (1999). Doi: https://doi.org/10.1146/annurev.matsci.29.1.327
50. J.-I. Hamagami, Y. Ato, K. Kanamura, Fabrication of highly ordered macroporous apatite coating onto titanium by electrophoretic deposition method, *Solid State Ionics*, **172**, 331 (2004). Doi: https://doi.org/10.1016/j.ssi.2004.02.046
51. A. R. Corni, I. Ryan, M. P. & Boccaccini, Electrophoretic deposition: from traditional ceramics to nanotechnology, *Journal of the European Ceramic Society*, **28**, 1353 (2008). Doi: https://doi.org/10.1016/j.jeurceramsoc.2007.12.011
52. P. Ducheyne, W. Van Raemdonck, J. C. Heughebaert, M. Heughebaert, Structural analysis of hydroxyapatite coatings on titanium, *Biomaterials*, **7**, 97 (1986). Doi: https://doi.org/10.1016/0142-9612(86)90063-3
53. I. Zhitomirsky, L. Gal-Or, Electrophoretic deposition of hydroxyapatite, *Journal of Materials Science: Materials in Medicine*, **8**, 213 (1997). Doi: https://doi.org/10.1023/A:1018587623231
54. V. Roether, J. A., Boccaccini, A. R., Hench, L. L., Maquet and R. Gautier, S. & Jerome, Development and in vitro characterisation of novel bioresorbable and bioactive composite materials based on polylactide foams and Bioglass for tissue engineering applications, *Biomaterials*, **23**, 3871 (2002). Doi: https://doi.org/10.1016/S0142-9612(02)00131-X
55. J. HUANG, L. DI SILVIO, M. WANG, K. E. TANNER, and W. BONFIELD, In vitro mechanical and biological assessment of hydroxyapatite-reinforced polyethylene composite, *Journal of Materials Science: Materials in Medicine*, **8**, 775 (1997). Doi: https://doi.org/10.1023/A:1018516813604
56. D. Zhitomirsky, J. A. Roether, A. R. Boccaccini, I. Zhitomirsky, Electrophoretic deposition of bioactive glass/polymer composite coatings with and without HA nanoparticle inclusions for biomedical applications, *Journal of Materials Processing Technology*, **209**, 1853 (2009). Doi: https://doi.org/10.1016/j.jmatprotec.2008.04.034
57. D. V. Pouya Amrollahia, Jerzy S. Krasinskib, Ranji Vaidyanathana, Lobat Tayebia, Handbook of Nanoelectrochemistry, *Handbook of Nanoelectrochemistry*, (2016). Doi: https://doi.org/10.1007/978-3-319-15207-3
58. L. C. W. Vandeperre, O. Van Der Biest, W. J. Clegg, Silicon carbide laminates with carbon interlayers by elec-

trophoretic deposition, *Key Engineering Materials*, **127 - 131**, 567 (1997). Doi: https://doi.org/10.4028/www.scientific.net/KEM.127-131.567

59. R. N. Basu, C. A. Randall, M. J. Mayo, Fabrication of dense zirconia electrolyte films for tubular solid oxide fuel cells by electrophoretic deposition, *Journal of the American Ceramic Society*, **84**, 33 (2001). Doi: https://doi.org/10.1111/j.1151-2916.2001.tb00604.x
60. T. Ishihara, K. Shimise, T. Kudo, H. Nishiguchi, T. Akbay, Y. Takita, Preparation of Yttriastabilised zirconia thin-films on strontium doped $LaMnO_3$ cathode substrate via Electrophoretic, *Journal of the American Ceramic Society*, **83**, 1921 (2000). Doi: https://doi.org/10.1111/j.1151-2916.2000.tb01491.x
61. İ. Aydın, A. İ. Bahçepınar, M. Kırman, and M. A. Çipiloğlu, HA Coating on Ti6Al7Nb Alloy Using an Electrophoretic Deposition Method and Surface Properties Examination of the Resulting Coatings, *Coatings*, **9**, 402 (2019). Doi: https://doi.org/10.3390/coatings9060402
62. X. Yin, C. Liang, and F. Ge, Electrodeposition of a YSZ-Yttria stabilized zirconia composite coating on a titanium bone implant, *International Journal of Electrochemical Science*, **13**, 822 (2018). Doi: https://doi.org/10.20964/2018.01.77
63. Ł. Pawłowski, M. Bartmański, G. Strugała, A. Mielewczyk-Gryń, M. Jażdżewska, and A. Zieliński, Electrophoretic Deposition and Characterization of Chitosan/Eudragit E 100 Coatings on Titanium Substrate, *Coatings*, **10**, 607 (2020). Doi: https://doi.org/10.3390/coatings10070607
64. M. Atiq Ur Rehman, Q. Chen, A. Braem, M. S. P. Shaffer, and A. R. Boccaccini, Electrophoretic deposition of carbon nanotubes: recent progress and remaining challenges, *International Materials Reviews*, **66**, 533 (2021). Doi: https://doi.org/10.1080/09506608.2020.1831299
65. E. Dlugon, W. Simka, A. Fraczek-Szczypta, W. Niemiec, J. Markowski, M. Szymanska, and M. Blazewicz, Carbon nanotube-based coatings on titanium, *Bulletin of Materials Science*, **38**, 1339 (2015). Doi: https://doi.org/10.1007/s12034-015-1019-4
66. I. Ahmed, H. Jaber, and S. Salih, Electrophoretic Deposition Used to Prepare and Analyze the Microstructure of Chitosan/Hydroxyapatite Nano-Composites, *Engineering and Technology Journal*, **39**, 1693 (2021). Doi: http://doi.org/10.30684/etj.v39i11.2181
67. A. K. Abed, A. M. Mustafa, and A. M. Resen, Assessment Corrosion and Bioactive Behavior of Bioglass Coating on Co-Cr-Mo Alloy By Electrophoretic Deposition For Biomedical Applications, *Corrosion Science and Technology*, **23**, 179 (2024). Doi: https://doi.org/10.14773/cst.2024.23.3.179
68. A. Fiołek, S. Zimowski, A. Kopia, and T. Moskalewicz, The Influence of Electrophoretic Deposition Parameters and Heat Treatment on the Microstructure and Tribological Properties of Nanocomposite Si3N4/PEEK 708 Coatings on Titanium Alloy, *Coatings*, **9**, 530 (2019). Doi: https://doi.org/10.3390/coatings9090530
69. S. Seuss, M. Lehmann, and A. R. Boccaccini, Alternating Current Electrophoretic Deposition of Antibacterial Bioactive Glass-Chitosan Composite Coatings, *International Journal of Molecular Sciences*, **15**, 12231 (2014). Doi: https://doi.org/10.3390/ijms150712231
70. A. Balamurugan, G. Balossier, J. Michel, and J. M. F. Ferreira, Electrochemical and structural evaluation of functionally graded bioglass-apatite composites electrophoretically deposited onto Ti6Al4V alloy, *Electrochimica Acta*, **54**, 1192 (2009). Doi: https://doi.org/10.1016/j.electacta.2008.08.055
71. Y. Guo, Y. Zhou, D. Jia, and Q. Meng, Fabrication and in vitro characterization of magnetic hydroxycarbonate apatite coatings with hierarchically porous structures, *Acta Biomaterialia*, **4**, 923 (2008). Doi: https://doi.org/10.1016/j.actbio.2008.02.014
72. Z.-C. WANG, L.-M. HUANG, Y. TANG, Y.-J. NI, C.-J. LIN, Preparation of Co-YSZ/HAp Nano-composite Coating on Ti Substrate by Electrochemical Method, *Acta Physico-Chimica Sinica*, **22**, 590 (2006). Doi: https://doi.org/10.3866/PKU.WHXB20060515
73. M. Kalisz, M. Grobelny, M. Mazur, M. Zdrojek, D. Wojcieszak, M. Świniarski, J. Judek, D. Kaczmarek, Comparison of mechanical and corrosion properties of graphene monolayer on Ti-Al-V and nanometric Nb_2O_5 layer on Ti-Al-V alloy for dental implants applications, *Thin Solid Films*, **589**, 356 (2015). Doi: https://doi.org/10.1016/j.tsf.2015.05.059
74. A. Mahapatro, Bio-functional nano-coatings on metallic biomaterials, *Materials Science and Engineering C*, **55**, 227 (2015). Doi: https://doi.org/10.1016/j.msec.2015.05.018