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Recent Advancements in Biocompatible Coatings for Metallic and Non-Metallic Biomaterials: A Review

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Metallic biomaterials are commonly utilized in medical implants due to their outstanding biocompatibility and corrosion resistance. These materials provide a strong foundation for various coating applications, with hydroxyapatite standing out due to its strong chemical resemblance to natural bone tissue, resulting in an exceptional biocompatibility. Recent research has highlighted the promise of composite coatings comprising hydroxyapatite combined with other hydroxides, particularly in the context of biomedical applications. These composite coatings exhibit notable strengths, enhanced adhesion properties, and superior corrosion resistance when they are applied to metallic biomaterials. Furthermore, the introduction of nanocomposite coatings has been proven to be effective in mitigating bacterial growth on surfaces. The application of composite coatings can result in increased surface roughness on coated samples. Crucially, the homogeneity within the structure of these composite coatings can enhance their ability to form strong bonds with bone tissues. This review synthesizes observed findings regarding composite coatings and their potential advantages in diverse applications. This review may furnish invaluable insights for researchers and practitioners actively engaged in diverse aspects of bone implant design and fabrication.

Keywords: *Hydroxyapatite, Composite coatings, Biocompatibility, Corrosion resistance, Electrophoretic deposition (EPD)*

1. Introduction

Metals play a vital role in orthopaedic applications, serving as essential components for fracture stabilization and prosthetic devices. In many developing countries, surgical-grade stainless steel (SS) is a widely utilized orthopaedic biomaterial. However, its suitability as a permanent orthopaedic implant is limited by its challenges in terms of corrosion resistance, osseointegration, and antibacterial properties [1]. This research addresses Indonesia's bone fracture problem, resulting from osteoporosis and accidents. It improves SS 316L implants by applying a HA coating through investment casting, resulting in a porous layer of varying thickness. Optimizing sintering at 900 ºC achieves the right calcium-phosphate balance, offering a cost-effective approach to enhance SS 316L for orthopedic implants and potentially contribute to solving the region's bone fracture issue [2]. Moreover, research by A. Fadli et al. reveals that precise adjustments to applied voltage and deposition time during electrophoretic deposition significantly impact the thickness of the HA coating on Stainless Steel 316L, affecting corrosion resistance and suitability for bone plates [3]. In another study, the goal is to enhance stainless steel's medical practicality by developing zein/hydroxyapatite (HA) composite coatings through Electrophoretic Deposition (EPD). The team optimized EPD parameters to successfully apply these coatings, improving corrosion resistance, water-attracting properties, and adhesion. Zein/HA coatings demonstrated the ability to form dense HA crystals, suggesting their promise for orthopedic applications and addressing stainless steel's corrosion limitations within the body [4].

Sol-gel coating, plasma spraying, and electrophoretic deposition (EPD) are the methods used to modify the surface properties of metallic implants. Among these

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methods, EPD stands out as a highly desirable and efficient approach due to its well-documented success rate. EPD enables the creation of functional materials and devices with a wide range of applications. It is characterized by minimal equipment requirements, short processing times, easy adjustability, cost-effectiveness, and the generation of dense particle depositions on the final product. Consequently, EPD facilitates the production of high-quality microstructures that can be tailored to complex geometries while affording precise control over morphology and thickness. EPD has been effectively employed for the fabrication of thin films using various ceramics [5].

The EPD process involves a sintering heat treatment step to yield high-density materials. To address concerns related to coating degradation and microstructure damage, a hybrid approach combining ceramic components with polymeric materials, such as chitosan, is applied to create organic-inorganic composite coatings. This innovative approach results in the development of a human bone replica, featuring a blend of organic and inorganic constituents ensconced within a biopolymer matrix composed of chitosan. Notably, chitosan exhibits structural similarity to glucosamine, a component of bone, ensuring optimal interaction with the substrate and serving as a binding agent for the layer components [6].

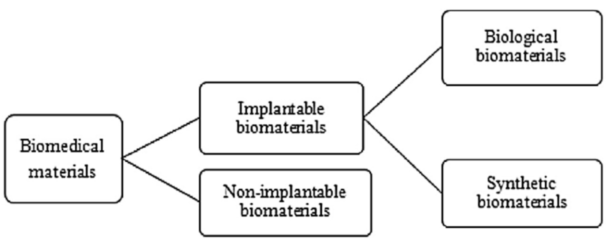

Fig. 1. Characterization of biomedical materials, biomaterials, and biological materials [7]

The crucial factor guiding the selection of biomaterials (as illustrated in Fig. 1) is their compatibility with the human body, necessitating significant properties that ensure long-term durability without triggering rejection responses [7]. This review is centred on a comprehensive evaluation of widely used metallic biomaterials, with a particular focus on their corrosion performance. The biomaterials under scrutiny encompass stainless steels, cobalt-chromium alloys, titanium, and its various alloy formulations [8].

Electrophoretic deposition (EPD) is a technique that involves the migration of charged particles suspended in a stable colloidal solution through a liquid medium under the influence of an electric field. Subsequently, these particles are deposited onto an oppositely charged conductive substrate, culminating in the creation of the desired material or device [9]. EPD stands out as an optimal colloidal process for fabricating ceramic structures, even when the solid content is relatively low. It is commonly utilized for the deposition of a wide range of metal oxide films, serving diverse applications [10]. A typical EPD cell includes a power supply,

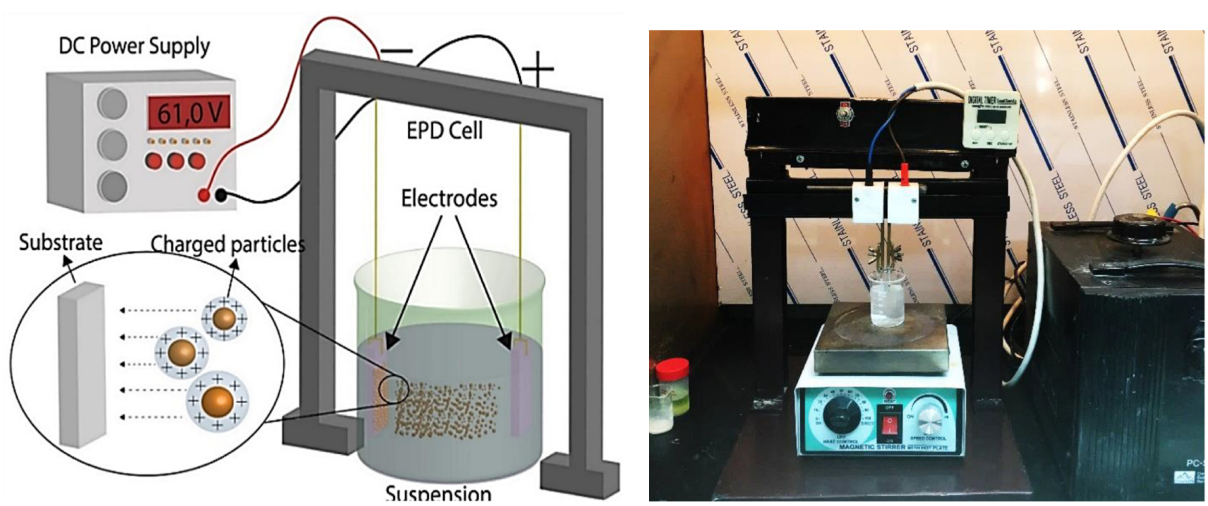

Fig. 2. EPD Cell Visual [11]

electrodes (anode and cathode) as visually demonstrated in Fig. 2 with the inclusion of an EPD cell [11].

This review systematically investigates the orthopaedic biomaterial coatings, commencing with an illuminating introduction highlighting the pivotal role of metallic materials in orthopaedic applications and the indispensable nature of coatings in this context. The paper adopts a structured approach, comprising distinct sections dedicated to specific coating types, namely Stainless Steel, Hydroxyapatite, Titanium, Zirconium, and Magnesium. Within each section, we explore the nuanced importance of these coatings, their application methodologies, and scrutinize composite coatings, subjecting various coating techniques to critical evaluation. We also conduct a comparative analysis into the utilizations of Biomaterials and their Mechanical Characteristics, facilitating a comprehensive understanding. This review ends with a thorough cross-comparison of all elucidated coatings, offering a synthesis of key insights and charting a course for future research endeavors in this domain.

2. Coating

2.1 Stainless steel Coating

Multifaceted world of coatings applied to orthopaedic biomaterials is investigated, with a particular focus on enhancing corrosion resistance and bioactivity, especially for materials like stainless steel [12]. The exploration encompasses a diverse array of coating methodologies, with a primary emphasis on electrophoretic deposition (EPD) and its profound implications for orthopaedic materials. Notable examples include the successful application of EPD to bioactive glass coatings on orthodontic stainless steel, a breakthrough that improves adhesion and preserves biocompatibility [13].

Furthermore, the innovative development of alginate-based antifouling coatings designed to combat marine biofouling, highlighting the versatility of EPD in tailored coatings [14]. Exploring further within the domain of EPD, the review investigates spinel coatings, which exhibit an extraordinary ability to prevent oxidation while safeguarding stainless steel interconnects against chromium migration, thus holding promise for corrosion mitigation [15].

Moreover, it is emphasized that the integration of silicon carbide (SiC) within hydroxyapatite (HA) coatings, ushering in a new era of vastly improved corrosion resistance in orthopaedic materials [16]. The inquiry extends to the development of degradable coatings endowed with antibacterial properties, finely tuned for surgical stainless steel, offering a promising avenue for averting nosocomial infections in clinical settings [1]. The evaluation of corrosion resistance and bioactivity in composite coatings, a complex fusion of polyvinyl alcohol (PVA), chitosan, and bioactive glass, is characterized by meticulous scrutiny, demonstrating the intricate interplay of these elements [17].

Furthermore, the influence of graphene oxide (GO) layer thickness is explored and its role in enhancing corrosion resistance when electrophoretically deposited onto stainless steel, providing valuable insights into material performance [18]. The comprehensive investigation culminates in the study of HA-chitosan-titania nanocomposite coatings, revealing nuances in deposition rates and surface attributes dependent on the solvent employed, thereby enriching our understanding

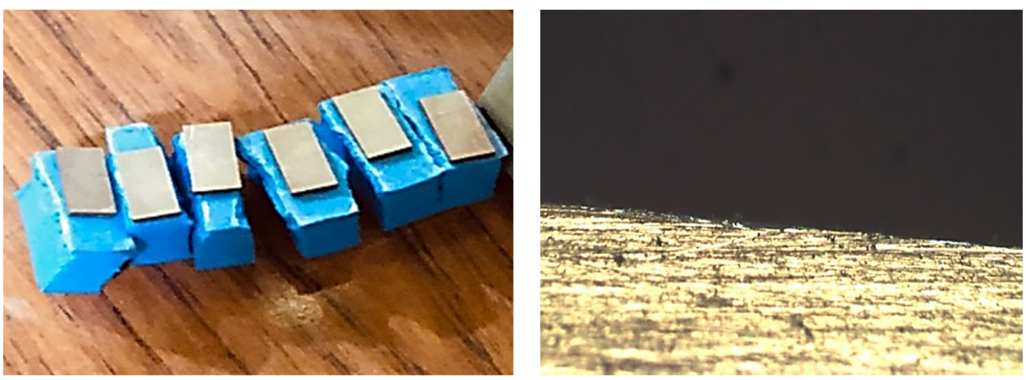

Fig. 3. Stainless steel Coating

of coating processes [19].

The application of TiO_2 coatings on medical-grade stainless steel is meticulously examined, showing to their remarkable efficacy in fortifying corrosion resistance, a development with promising implications for orthopaedic applications [20]. The paper introduces an inventive composite coating comprising chitosan-baghdadite nanoparticles. This innovative coating not only showcases exceptional hydrophobic characteristics, making it highly water-resistant, but it also demonstrates remarkable biocompatibility, indicating its suitability for various biological applications. [21]. These combined discoveries mark a substantial contribution to the progress of orthopaedic biomaterial coatings, potentially bringing about improved resistance against corrosion, increased compatibility with biological systems, and potent antibacterial features within the field of orthopedic applications.

2.2 Hydroxyapatite Coating

Next, the study explores into the wide range of hydroxyapatite (HA) coatings on different surfaces. A special attention to how the applied voltage and deposition time affect these coatings, examining these factors closely. Although the results are interesting, there's room for a deeper discussion and analysis to enhance our understanding of this complex field.

The initial study centres on the coating of stainless steel 316L with HA. This investigation uncovers that as deposition time extends, thicker HA layers ensue, with measurements of 35 μm, 50 μm, and 60 μm recorded at deposition times of 10, 20, and 30 minutes, respectively, at 50 volts. Of significance, these coatings demonstrate an effective mitigation of stainless-steel corrosion, reducing corrosion rates to 0.91, 0.704, and 0.56 mpy for deposition times of 10, 20, and 30 minutes at 50 volts. Nonetheless, an analysis of potential limitations in the research methodology, sample size, or the generalizability of findings is noticeably absent. [3]

In another study, electrophoretic deposition (EPD) of nano-hydroxyapatite (nanoHA) coatings adorned with silver nanoparticles (nanoAg) is explored. This investigation researches into mechanical and chemical properties, considering EPD voltage and the presence of nanoAg. The study reveals a fascinating increase in the release rate of silver nanoparticles with prolonged exposure time and higher EPD voltage. It's worth noting that corrosion currents are significantly elevated for undecorated nanoHA coatings, approaching levels seen in the substrate, while resistance to nano scratching improves with thicker coatings. Nevertheless, this study leaves potential biases or limitations unaddressed [22].

In a different research endeavour, the synthesis of bioactive hydroxyapatite/multiwalled carbon nanotube (HA/MWCNT) composite coatings on 316L SS implants is examined via a spray pyrolysis technique. Results indicate enhanced antibacterial activity and commendable corrosion resistance in simulated body fluid, spotlighting the potential for biomedical applications. However, a critical discussion concerning the generalizability of these findings or the challenges encountered during the spray pyrolysis process would offer valuable insights [23].

The exploration of hydroxyapatite (HA)–chitosan–titania nanocomposite coatings via electrophoretic

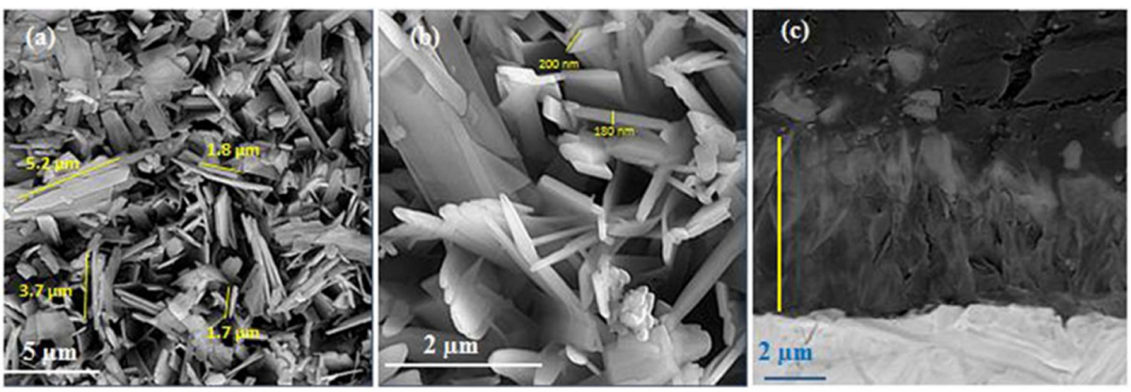

Fig. 4. Fe-SEM micrographs of Hydroxyapatite: a) HA morphology and microstructure, b) HA at higher magnification

deposition (EPD) employing different solvents highlights the impact of solvent selection on deposition rate and surface smoothness. Although the study accentuates higher corrosion resistance when ethanol is used as a solvent, it falls short of delving into potential drawbacks or limitations associated with this method [19].

A study scrutinizing the deposition of HA coatings on stainless steel 316L provides invaluable insights into the influence of voltage, withdrawal speed, and sintering temperature. However, it falls short in providing a thorough discussion of potential challenges encountered during the sintering process and the implications of a phase transformation at elevated temperatures [24].

The optimization of SiC concentration in HA coatings on AISI 316L stainless steel alloy offers promising results in terms of heightened corrosion resistance and enhanced mechanical properties. Nevertheless, a comprehensive discussion of potential trade-offs or challenges associated with the incorporation of SiC remains elusive [16].

In a different approach, hydroxyapatite (HA) is applied to the surface of 316L SS using the investment casting technique The study reveals the influence of sintering temperature on coating thickness and hardness. However, it refrains from researching into potential drawbacks or complexities linked to the investment casting method [2].

2.3 Titanium Coating

In the pursuit of creating superhydrophobic TiO_2/TMPSi (trimethoxy(propyl)silane) composite coatings on AISI 316L stainless steel, a two-step process was executed. Firstly, TiO_2 nanoparticles (P25) were electrophoretically deposited (EPD) from a colloidal suspension of TiO_2 in acetylacetone, bolstered by iodine. Subsequently, a dip coating using varying concentrations of TMPSi in an aqueous ethanol solution was performed. An exceptional achievement worth highlighting is the successful elimination of surface cracks during the EPD process. This involved carefully applying controlled potential over a voltage range from 5 V to 30 V, followed by precise drying. This intricate process resulted in a significant reduction in surface roughness, leading to a tangible decrease in contact angles (WCA) and a notable increase in sliding angles (SA), with precise measurements of WCA=150º and SA=5.6º [25].

Transitioning to this research, where the primary focus is to scrutinize the implications of introducing WO_3 into TiO_2-WO_3 composite coatings on their mechanical, tribological properties, and corrosion resistance. Particularly noteworthy is the remarkable performance of the thin film with the highest tungsten content, designated as $(Ti_5OW_5O)O_x$, which exhibited superior mechanical properties compared to the pristine TiO_2 coating. Furthermore, augmenting the WO_3 content within the composite coating resulted in a pronounced enhancement in tribological properties [26].

The next investigation leads to Pd-Ni/TiO_2 composite coatings, synthesized through an electrodeposition method on 316L stainless steel. Of particular note is the microhardness of these Pd-Ni/TiO_2 composite coatings, which exhibited enhancement in tandem with increasing TiO_2 content. It is important to highlight that the addition of 5 g L^{-1} TiO_2 particles to the electrolyte resulted in a substantial improvement in corrosion resistance when exposed to a sulfuric acid solution at 60 ºC, surpassing that of the Pd-Ni alloy coating. However, it is noteworthy that further increments in TiO_2 content did not yield additional improvements in corrosion resistance [27].

This research focus on thin coatings deposited onto biocompatible 316L steel with the aim of enhancing wear resistance. The results gleaned from this study suggest a discernible correlation between the formation of a TiO_2 film and thermal oxidation time. Impressively, the coating exhibited a favourable impact on wear resistance, which was notably influenced by surface roughness. Also, this study meticulously evaluated other coating attributes, including surface topology altered by TiO_2 diffusion and nano hardness [28].

The microstructure, phase composition, and morphology under different voltages (20, 30, and 40 V) were explored in this study. Advanced techniques such as scanning electron microscopy (SEM), X-ray diffraction (XRD), and atomic force microscopy (AFM) played pivotal roles. The experimental findings emphasized that increasing the voltage led to a concomitant increase in coating thickness and the emergence of cracks. An interesting observation is that the film generated under 30 V exhibited the lowest corrosion current density (I_{corr}) value of 0.21 μA cm^{-2}, coupled with the lowest corrosion potential (E_{corr}) value of 111.89 mV. These favourable outcomes were predominantly attributed to a remarkable reduction in micro-pore density within the coating [29].

Now, shifting the focus to the subsequent study, the fabrication of a hydrophobic two-dimensional (2D) TiO_2/MOS_2 nanocomposite coating on AZ31B magnesium alloy, utilizing an electrophoretic deposition method. The corrosion experiments conducted shed light on the remarkable anticorrosion performance exhibited by the hydrophobic 2D TiO_2/MOS_2 coating. This coating boasted a corrosion potential (Ecorr) of −0.85 VAg/AgCl and a corrosion current density (Icorr) of 6.73×10^{-8} A·cm^{-2}. These findings hold significant promise for the application of TiO_2/MOS_2 films in safeguarding magnesium alloys against corrosion [30].

Intricacies surrounding titanium dioxide thin films immobilized on treated stainless steel using the pulsed electrophoretic deposition technique surface in the subsequent study. Optimization was achieved through the implementation of a desirability function, enhancing multiple responses of the TiO_2 thin film. Under the optimized conditions, the decolorization efficiency of the tested dye solution soared to an impressive 82.75%, while critical charges LC1, LC2, and LC3 were meticulously determined to be 5.9 N, 12.5 N, and 16.7 N, respectively [31].

Titania (TiO_2) across various applications, such as photocatalytic and photovoltaic devices, sensors, biomedical coatings, and its role as a protective agent against corrosion and oxidation, this review consolidates diverse facets related to the fabrication of TiO_2 coatings through electrophoretic deposition (EPD) of n-TiO_2. In doing so, it researches into recent advances and casts a visionary light on forthcoming research directions and innovations pertaining to n-TiO_2 EPD [32].

The present study meticulously centres on the preparation of highly porous and electrically active TiO_{2-x} ceramic scaffolds via the polymer replica method. Extensive in vitro studies validate the cytocompatibility of these scaffolds, highlighting their potential for enhancing cell spreading. Consequently, these TiO_{2-x} scaffolds emerge as promising candidates for applications in bone tissue regeneration, as they offer the unique ability to provide electrical stimuli that enhance the bone healing process [33].

Direct current electrophoretic deposition (EPD) emerges as the preferred technique for coating the intricate 3D porous structure of TiO_{2-x} ceramic Utilizing nanocrystalline TiO_2 particles, the deposition time and applied voltage were varied, resulting in a nanocrystalline TiO_2 coating strategy that imparts bioactive properties to the 3D scaffold. This strategic approach facilitates the formation of spherical hydroxyapatite particles on the coated scaffolds following immersion in simulated body fluid. Crucially, in vitro cell studies did not reveal any cytotoxic effects associated with the nanocrystalline TiO_2-coated scaffolds [34]. proliferation was studied for Ti porous scaffolds manufactured via powder metallurgy and sintering as shown in Fig. 3 [1].

The AC impedance behavior of silicon-hydroxyapatite doped film on the Ti–35Nb–xZr alloy by EB-PVD method was investigated. The Si–HA composite coating layers were formed from Si of 0.8 wt% with HA by EB-PVD method. The surface of Si–HA-coated Ti–35Nb–10Zr alloy showed rougher morphologies after heat treatment than as-surface with the coated thickness around 100 nm. Si–HA-coated surface showed a good corrosion resistance than HA single-coated and non-coated surface [63]. In this study, photoelectrochemical

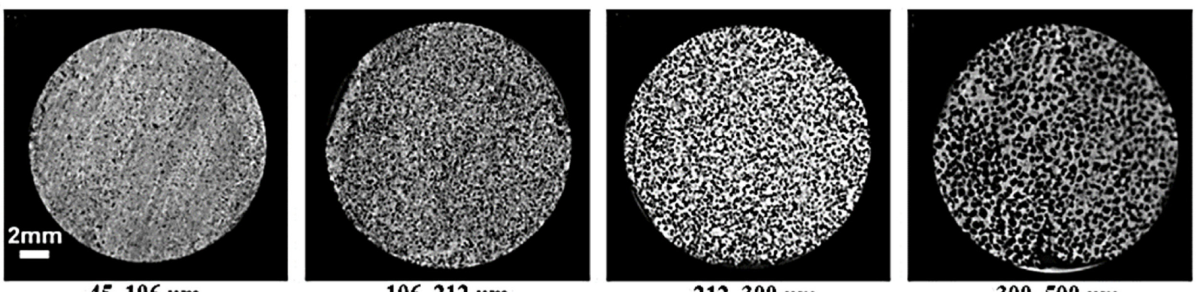

Fig. 5. Titanium scaffolds featuring 70% porosity and varying pore size distributions [35]

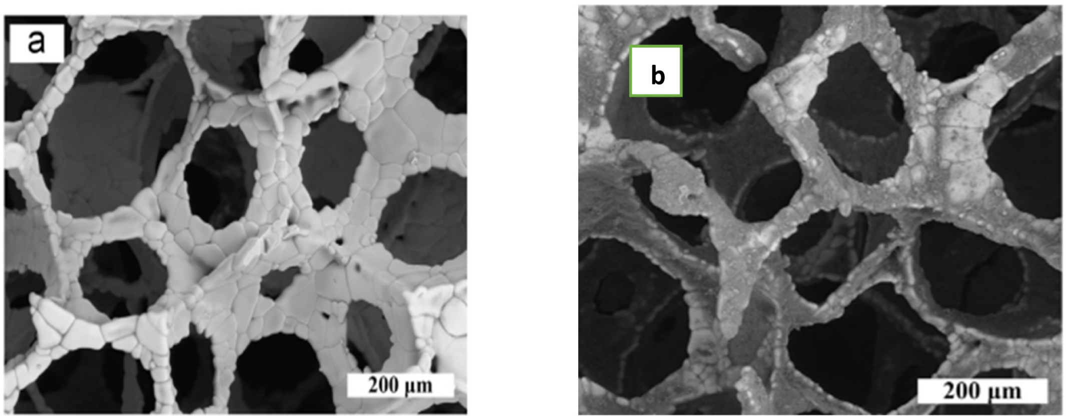

Fig. 6. FE-SEM micrographs of (a) TiO_2 scaffold, (b) HAp/PVA coated TiO_2 scaffold

analysis of bioactive material coated nanotubular surface of Ti–30Nb–xZr alloy has been investigated using a potentiostat and a Xenon lamp. Hydroxyapatite (HA) was coated on nanotubular alloy by electron-beam physical vapor deposition (EB-PVD) method. The microstructures of the Ti–30Nb–3Zr and Ti–30Nb–15Zr alloys showed an equiaxed grain structure with needle-like α phase in the β phase grains. The study suggested that the photo functionalization reaction strongly depends on the structure of oxide surface, crystallinity of hydroxyapatite and alloying elements [64]. The aim of this study was to investigate the morphology change of HA films on highly ordered nanotubular Ti–Nb–Hf alloys as a function of electrochemical deposition cycle. The HA-deposited surface after nanotube formation on the Ti–Nb–Hf alloys should provide improved cell proliferation at a higher rate than on the nanotubular and bulk titanium alloy surfaces Titanium dental implants are often coated with HA to improve osseointegration, ensuring a stable and long-lasting connection between the implant and jawbone. HA-coated implants are used in spinal fusion procedures to promote bone growth and achieve stable spinal fusion [65]. The surface characteristics of hydroxyapatite coatings on nanotubular Ti–25Ta–xZr alloys prepared by electrochemical deposition for dental implants have been investigated using various methods. The Ti–25Ta–xZr alloys were prepared by an arc melting furnace, homogenized for 12 h at 1000 ºC in an argon atmosphere, and then water-quenched. Surface characteristics were observed by optical microscopy, X-ray diffraction, Microstructures of the Ti–25Ta–xZr alloys changed from α″ phase to β phase, and the phases changed. The arrangement of nanotubes changed HA precipitates also changed in morphology [66].

2.4 Zirconium Coating

The synthesis of both pure HA and HA-ZrO_2-TiO_2 nanocomposite coatings was achieved in previous study, hereafter referred to as HZT coatings, by merging two conventional electroplating techniques. Analysis using Energy-Dispersive X-ray Spectroscopy (EDS) clearly demonstrated that an increased concentration of nanoparticles in the solution led to a more substantial deposition of nanoparticles within the composite coating. Consequently, this resulted in a significant reduction in porosity, with porosity levels decreasing dramatically from 46% for the HA coating to a mere 6% for the HZT_2 coating. Moreover, Electrochemical Impedance Spectroscopy (EIS) data provided compelling evidence that the incorporation of nanoparticles led to a substantial improvement in the corrosion resistance of these coatings. Notably, among all the coatings, the HZT_2 coating exhibited the highest charge transfer resistance. Complementing these findings, Field Emission Scanning Electron Microscope (FE-SEM) observations confirmed the bioactive behaviour of the coatings, as natural hydroxyapatite deposits formed during the immersion process [36].

Transitioning to current investigation, the central focus revolves around characterizing hydroxyapatite, zirconia, and graphene oxide nanocomposite coatings applied to a titanium substrate through the electrophoretic deposition method. The corrosion test results have unequivocally showcased a substantial enhancement in the surface's corrosion resistance facilitated by the utilization of these nanocomposite coatings. These findings are further corroborated by antibacterial tests, which underscore the remarkable efficacy of nanocomposite coatings in curtailing bacterial growth on the surface [37].

In a parallel study, a composite coating comprising calcium phosphate and zirconia ($CaPh/ZrO_2$) to the AZ91D magnesium alloy, employing a combination of electrolytic and annealing methods. The intermediate ZrO_2 layer played a pivotal role in enhancing the adhesion strength of the top CaPh layer on AZ91D, primarily by facilitating the condensation of hydroxyl bonds within the Zr(OH)4 precursor. Furthermore, the top CaPh layer exhibited a remarkable ability to enhance cell adhesion and proliferation, providing a stark contrast to the reduced cell count observed on uncoated AZ91D, attributable to its higher corrosion rate [38].

In the research of the fabrication of hydroxyapatite coatings and composite hydroxyapatite coatings containing nanoparticles, using a single-step electrodeposition technique. Notably, two distinct compounds were introduced, titania and zirconia, into the matrix. Polarization and immersion tests have showed the superior attributes of these composite coatings when compared to pure hydroxyapatite coatings. Furthermore, it is essential to recognize that the characteristics of the hydroxyapatite matrix were not solely influenced by the type of compositing agent but also by the additive content, resulting in a cascade of changes such as reduced coating thickness, heightened crystallinity, altered morphology, a more positive corrosion potential (E_{corr}), and a reduced porosity ratio in comparison to pure hydroxyapatite [39].

Transitioning to a novel approach, a titanium-based Ti-21Nb-15Ta-6Zr alloy coated with hydroxyapatite-zirconia (HA-ZrO_2) through the innovative pulsed laser deposition (PLD) technique was characterized. The evaluation of its corrosion resistance, conducted within a simulated physiological Ringer's solution at 37 ºC, suggests that the HA-ZrO_2 coated Ti-21Nb-15Ta-6Zr alloy holds the promise of exerting negligible effects on biochemical and cellular interactions at the bone-implant interface. Furthermore, this coating may play a pivotal role in facilitating osseointegration [40].

The incorporation of zirconia and hydroxyapatite has paved the way for the development of highly suitable composites for dental implants, offering improved physicochemical properties. In this comprehensive review, valuable insights into methodologies and exemplary instances of designed composites tailored for dental implant applications have been highlighted. Various methods for surface modification of zirconia infused with hydroxyapatite, including sol-gel, hot isostatic pressing, plasma spraying, and electrophoretic deposition have been emphasized. The endeavour is to shed light on the advantages, disadvantages, biocompatibility, strength, and the osteointegration and bio integration properties of these innovative composites, thus providing invaluable information for the dental field [41].

Zirconia/hydroxyapatite composites were created by blending hydroxyapatite (HA) with ZrO_2 nanoparticles through a precipitation synthesis method. When subjected to simulated body fluid (SBF) testing, the Ca-ZrO_2/HA composites exhibited superior bioactivity compared to the Y-ZrO_2/HA composites. The osteoblast cells displayed more extensive adhesion to the Ca-ZrO_2/HA composites than to the Y-ZrO_2/HA ones. These findings show the importance of microstructure and chemical composition in optimizing the mechanical and biological suitability of these composites for use in bone repairs [3] .

Another research embarked on modifying ZrO_2 glass by incorporating varying amounts of bioactive and biocompatible hydroxyapatite (HAp). The synthesis of ZrO_2/HAp composites via the sol-gel method, subjected to varying temperatures to induce chemical structural modifications, has revealed intriguing insights. Notably, bioactivity was found to increase with both HAp content and the temperature employed during thermal treatment. Simultaneously, biocompatibility showed signs of improvement with increasing heat treatment, while remaining unaffected by alterations in HAp content [43].

In parallel, ZrO_2-10 mol.% SiO_2 composite coatings on 316L stainless steel have been successfully produced. The composite particles, meticulously prepared using the sol-gel processing method, were electrophoretically deposited onto a pre-treated substrate and subsequently sintered at 1100 ºC. A comprehensive examination, conducted in a simulated body fluid solution, has demonstrated that the highest barrier effect was achieved when anodically oxidized surfaces were post-coated. This particular sample exhibited the lowest corrosion current density of 0.95 nA cm^{-2} after a 24-hour immersion period [44].

The most recent study was dedicated to the development of a nano-sized coating with the potential to prevent premature failures of NiTi components and the release of nickel into the human body. The findings indicate that the deposition process, utilizing both $ZrOCl_2$ and $ZrO(NO_3)_2$ aqueous solutions, has resulted in the reduction of surface roughness and an improvement in the corrosion resistance of superelastic NiTi wires. Furthermore, the addition of PolyDADMAC to aqueous and methanolic electrolytes led to a more uniform coating surface and increased corrosion resistance when subjected to Hank's solution. Notably, ZrO_2 deposition continued to enhance the corrosion resistance of NiTi wires, even in the absence of prior electrolytic polishing [45].

The effects of amorphous SiO_2 on porosity and interlayer formation within sintered ZrO_2-SiO_2 composite coatings were investigated. The results gleaned from this study illuminate how SiO_2 serves to densify the coating and reduce the volume fraction of interconnected pores. The corrosion performance of ZrO_2-SiO_2 coatings exhibited marked improvement as the SiO_2 content increased, a result attributed to the heightened barrier effect stemming from the thicker interlayer and lower permeability, supported by a lower percentage of interconnected pores [46].

A detailed examination of the electrophoretic deposition (EPD) process involving Zirconia nanoparticles suspended in a mixture of different solvents, namely ethanol, butanol, and isopropanol, with the addition of Triethanolamine (TEA) as a dispersant has been undertaken. Through the utilization of potentiodynamic polarization and electrochemical impedance spectroscopy (EIS) methods, the enhanced corrosion resistance of the coated substrates in saline solution at 25 ℃ has been obtained. Notably, corrosion resistance was found to increase with the reduction in applied DC voltage during the EPD process and with the use of butanoic suspension [47].

2.5 Magnesium Coating

The primary objective of this study was to develop a porous composite material by amalgamating magnesium with nano-hydroxyapatite (nHA) to attain mechanical properties suitable for specific applications. The investigation showed that composites containing 2 and 4 wt% of nHA showcased the most desirable characteristics. These particular composites exhibited a yield strength approximately twice as high and a plateau stress roughly three to four times greater than that of pure magnesium. In addition, their elastic modulus, measured at 0.25 GPa, fell within the typical range observed in cancellous bone. Notably, the degradation rate of composites containing 2-4 wt% of nano-hydroxyapatite decreased by approximately 35 to 40 percent in comparison to pure magnesium. This implies that the Mg/nHA composite, especially those with 2-4 wt% of hydroxyapatite, holds substantial promise as an alternative material for degradable load-bearing implants [48].

In the scope of another research, an evaluation of the stability of magnesium-doped hydroxyapatite/chitosan (MHC) suspensions, synthesized via the sol-gel method, employing non-destructive ultrasound measurements has been conducted. The results yielded valuable insights into the surface morphology and chemical composition of the MHC coatings, indicating their capacity to rapidly foster the development of a new apatite layer when immersed in DMEM. Initial in vitro biological assessments underscored the noncytotoxic nature of the tested samples on primary osteoblast and HCT-8 cell lines, signifying their potential in minimizing the risk of infections and postoperative inflammation. The coatings established on the foundation of the MHC composite have the potential to significantly enhance the success rate of implants, thereby contributing to the field of medical implantation [49].

2.6 Composite coatings

An extensive exploration of advanced coating technologies was embarked. A wide range of coatings were created, and their potential utility across various fields was thoroughly evaluated. The reviews can be divided into several key areas, each contributing to our understanding of advanced coatings and their wide-ranging implications.

In the first endeavour, it is successfully synthesized both pure hydroxyapatite (HA) coatings and HA-ZrO_2-TiO_2 nanocomposite coatings, known as HZT coatings, by merging two conventional electroplating techniques. A meticulous analysis using energy-dispersive X-ray spectroscopy (EDS) unveiled a fascinating correlation: an increased concentration of nanoparticles in the solution led to a more substantial deposition within the composite coating. This, in turn, resulted in a remarkable reduction in porosity, with the porosity decreasing significantly from 46% for the HA coating to a mere 6% for the HZT_2 coating. Moreover, the electrochemical impedance spectroscopy (EIS) data demonstrated a noteworthy enhancement in the corrosion resistance of the coatings with nanoparticle incorporation, with the HZT_2 coating displaying the highest charge transfer resistance among all the coatings. A field emission scanning electron microscopy (FE-SEM) observations further confirmed the coatings' bioactive behaviour, evident through the formation of natural hydroxyapatite deposits during immersion [36].

An ongoing investigation is dedicated to characterizing nanocomposite coatings of hydroxyapatite, zirconia, and graphene oxide applied to titanium substrates using the electrophoretic deposition method. In this context, the corrosion tests have revealed a substantial enhancement in surface corrosion resistance facilitated by the application of these nanocomposite coatings. Additionally, the antibacterial tests have demonstrated the coatings' effectiveness in reducing bacterial growth on the surface [37].

In another facet of this research, hydroxyapatite coatings and composite hydroxyapatite coatings containing nanoparticles were fabricated using a one-step electrodeposition method. Notably, two distinct compounds were introduced, titania and zirconia, into the matrix. A comprehensive evaluation, including polarization and immersion tests, has unveiled that composite coatings exhibit superior properties compared to pure hydroxyapatite coatings. These improvements encompass reduced coating thickness, increased crystallinity, altered morphology, a more positive corrosion potential (Ecorr), and a reduced porosity ratio compared to pure hydroxyapatite [39].

Taking a pioneering approach, hydroxyapatite-zirconia (HA-ZrO_2) coatings was applied to a titanium-based Ti-21Nb-15Ta-6Zr alloy, employing the innovative pulsed laser deposition (PLD) technique. An evaluation of corrosion resistance, conducted within a simulated physiological Ringer's solution at 37 ºC, suggests that the HA-ZrO_2 coated alloy holds the promise of exerting negligible effects on biochemical and cellular interactions at the bone-implant interface, potentially facilitating osseointegration [40].

The exploration has extended into the realm of dental implant technology. The incorporation of zirconia and hydroxyapatite has given rise to highly suitable composites with improved physicochemical properties. This comprehensive review offers insights into various methodologies for surface modification, including sol-gel, hot isostatic pressing, plasma spraying, and electrophoretic deposition. This exploration delves deeply into the advantages, disadvantages, biocompatibility, strength, as well as osteointegration and bio integration properties of these innovative composites, offering invaluable information for dental applications [41].

In this recent work, main focus in on modifying ZrO_2 glass by incorporating varying amounts of bioactive and biocompatible hydroxyapatite (HAp). The synthesis of ZrO_2/HAp composites via the sol-gel method, followed by subjecting them to varying temperatures to induce chemical structural modifications, has yielded intriguing results. The findings demonstrate that bioactivity increases with both HAp content and the temperature used for thermal treatment, while biocompatibility improves with heating but remains unaffected by alterations in HAp content [42].

On the other hand, ZrO_2-10 mol.% SiO_2 composite coatings on 316L stainless steel is produced using the sol-gel processing method. These composite particles were then electrophoretically deposited on a pre-treated substrate and subsequently sintered at 1100 ºC. The extensive corrosion studies in a simulated body fluid solution have indicated that the highest barrier effect was achieved on the anodically oxidized surface post-coating, revealing the lowest corrosion current density of 0.95 nA cm^{-2} after 24 hours of immersion [44].

The recent study has been dedicated to developing a nano-sized coating with the potential to prevent premature failures of NiTi components and the release of nickel into the human body. The findings suggest that the deposition process, involving both $ZrOCl_2$ and $ZrO(NO_3)_2$ aqueous solutions, has led to a reduction in surface roughness and an enhancement in the corrosion resistance of super elastic NiTi wires. Notably, the addition of PolyDADMAC to aqueous and methanolic electrolytes has resulted in a more uniform coating surface and increased corrosion resistance when subjected to Hank's solution. Impressively, ZrO_2 deposition continues to enhance the corrosion resistance of NiTi wires, even in the absence of prior electrolytic polishing [45].

In this investigation, the effects of amorphous SiO_2 on porosity and interlayer formation within sintered ZrO_2-SiO_2 composite coatings were refined. The results gleaned from this study shed light on how SiO_2 serves to densify the coating and reduce the volume fraction of interconnected pores. The corrosion performance of ZrO_2-SiO_2 coatings has exhibited marked improvement as the SiO_2 content increased, attributed to the heightened barrier effect stemming from the thicker interlayer and lower permeability, supported by a lower percentage of interconnected pores [46].

A detailed examination of the electrophoretic deposition (EPD) process involving Zirconia nanoparticles suspended in a mixture of different solvents, namely ethanol, butanol, and isopropanol, with the addition of Triethanolamine (TEA) as a dispersant has been conducted. Through the utilization of potentiodynamic polarization and electrochemical impedance spectroscopy (EIS) methods, the enhanced corrosion resistance of the coated substrates in saline solution at 25 ºC has gained valuable insights. Notably, corrosion resistance was found to increase with the reduction in applied DC voltage during the EPD process and with the use of butanoic suspension [47]. Fig. 4 illustrates how adhesion and cohesion strength interact between the adhesive material and the substrates [50].

The application of a chitosan-hydroxyapatite composite coating via electrophoretic deposition (EPD) brought about a remarkable transformation in the anatase samples. Notably, the concentration of hydroxyapatite in the suspension emerged as a crucial factor influencing the morphology of the deposited coating. Intriguingly, the introduction of chitosan-hydroxyapatite composite coatings resulted in an increased surface roughness when compared to the original ATO layers. A comprehensive analysis of the EPD coatings, including examinations of their morphology, compositional makeup, and crystalline phases, unequivocally confirmed the successful coating of anodic TiO_2 samples with a chitosan-hydroxyapatite composite. This achievement holds substantial promise for creating a more conducive surface for interactions with bone [51].

In this manuscript, the development of a hydroxyapatite coating incorporating strontium and copper substitutions (SrCuHA) on commercially pure titanium (CP-Ti) and thoroughly investigate its effects on antibacterial properties as well as its compatibility with in vitro cytocompatibility was explored. The in vitro electrochemical corrosion studies yielded intriguing results, as the SrCuHA coating exhibited remarkable resilience in simulated body fluid (SBF), showcasing superior corrosion resistance and a lower corrosion penetration rate compared to the bare CP-Ti substrate. The SrCuHA coatings also demonstrated antibacterial properties, with the ability to partially inhibit Escherichia coli growth in the initial days, attributed to the copper substitution within the coating.

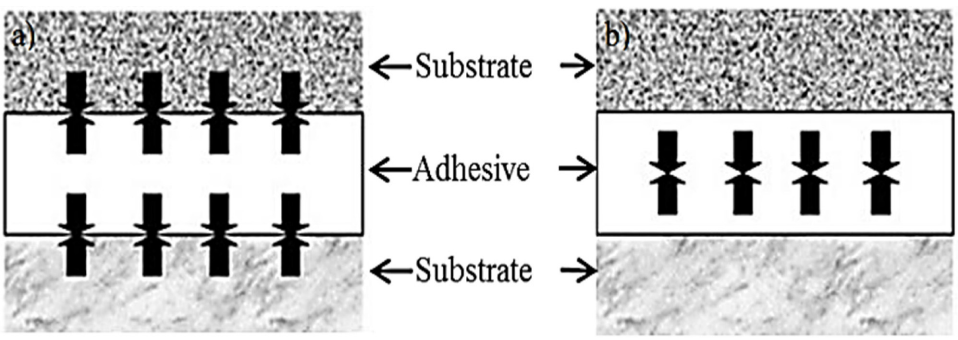

Fig. 7. The mechanisms of (a) adhesion and (b) cohesion strength between the adhesive and the substrates [50]

Moreover, an increase in osteoblast adhesion, proliferation, and alkaline phosphatase activity was noted, signifying significant potential for applications in the fields of orthopedics and dentistry [52].

This study introduced an innovative approach involving ultrasound-assisted pulse electrodeposition to create the GO-HA coating on the anodized and heat-treated surface of titanium. The results of nanoindentation tests were particularly noteworthy, demonstrating the highest nano-hardness (3.08 GPa) and elastic modulus (41.26 GPa) for the GO-HA coating prepared using this ultrasound-assisted method. Subsequent analysis via EDS and FTIR unveiled the presence of both GO sheets and highly reactive OH· groups. Besides, pore size distribution diagrams calculated from the N_2 adsorption-desorption isotherms indicated a reduction in the pore size of HA crystals within the electro-deposited GO-HA sample. Ultimately, the combination of anodizing, heat treatment, and the incorporation of GO sheets into the coating collectively contributed to a significant enhancement in the corrosion protection of titanium [53].

In this investigation, the application of ultrasound-assisted pulse electrodeposition was expanded to fabricate a coating composed of graphene oxide (GO) and hydroxyapatite (HA) on TiO_2 nanotubes. The pre-treatment of the substrate and the integration of GO sheets into the HA coating played a pivotal role in enhancing the bonding strength at the interface between the coating and the substrate. Remarkably, the findings from fibroblast cell culture and the 3-(4,5-dimethylthiazolyl-2)-2,5-diphenyltetrazolium bromide (MTT) assay after 2 days highlighted a higher percentage of cell activity for the GO-HA coated sample. Furthermore, a 7-day exposure to simulated body fluid (SBF) showcased a faster rate of apatite precipitation on the GO-HA coating, outperforming both the HA coating and pre-treated titanium [54].

The research endeavors resulted in the development of a novel implant coating material incorporating graphene oxide (GO), collagen (COL), and hydroxyapatite (HA), facilitated by tannic acid through the electrodeposition process. These coatings, namely HA, HA-GO, and HA-GO-COL, significantly bolstered corrosion resistance by forming a protective barrier layer on the $Ti_{16}Nb$ alloy surface. Impressively, HA-GO-COL exhibited the highest corrosion resistance, attributed to its compact and uniform coating structure. Also, the inclusion of graphene oxide in the coatings enhanced antibacterial properties compared to the GO-free coating against S. aureus. The combination of GO and collagen with the HA coating resulted in increased strength. While GO addition to the HA coating reduced the viability of $3T_3$ fibroblast cells, the incorporation of collagen into HA-GO enhanced cell adhesion and viability [55].

Bio-ceramic composite coatings were meticulously deposited onto surgical-grade 316L stainless steel substrates using an in-situ electrolytic method. This process involved applying a voltage of -1.5 V for a duration of 30 minutes while employing a three-electrode setup. Subsequent in-vitro corrosion studies conducted on these meticulously crafted bio-ceramic composite coatings revealed their exceptional corrosion protection performance in a simulated body fluid environment. Moreover, these coatings exhibited a notable acceleration in apatite mineralization, thereby enhancing their affinity for bonding with bone tissue. These compelling findings highlight the potential effectiveness of electrochemical deposition as a viable method for orthopaedic repair and replacement applications [56].

In this study, a comprehensive assessment of the performance of talc derived from soapstone, an economically viable and environmentally friendly material was conducted. The feasibility as a substitute for reduced graphene oxide in strengthening fragile hydroxyapatite coatings was evaluated. The battery of tests, spanning corrosion resistance, wear resistance, and biocompatibility, yielded promising results. Talc demonstrated the capacity to effectively replace reduced graphene oxide without compromising the mechanical integrity, anticorrosion properties, or biocompatibility of the composite coatings. These findings shed light on the promising prospects of utilizing talc from soapstone in various biomedical applications [57].

As part of the research, electrophoretic deposition (EPD) was combined with a reaction bond sintering process to administer a composite coating comprising hydroxyapatite (HA), titanium (Ti, 20 wt%), and multi-walled carbon nanotubes (MWCNTs, 1 wt%) onto a NiTi alloy substrate. Detailed analysis using field-emission scanning electron microscopy (FE-SEM) unveiled a substantial enhancement in the sintering quality of the HA coating when combined with titanium. Besides, the hardness and adhesion strength of the HA coating exhibited significant improvements upon the incorporation of titanium and MWCNTs (HA-Ti(20wt%)-MWCNTs (1wt%) coating). Additionally, biological tests demonstrated remarkable enhancements in apatite formation and the growth of bone cells on the HA coatings containing titanium and MWCNTs [58].

The primary objective of this study was to enhance the resistance of the Ti_6Al_4V alloy to bio-corrosion. A solution was explored that entailed applying a sole layer of nano hydroxyapatite (HAP) and nano yttria-stabilized zirconia (YSZ) through the process of electrophoretic deposition (EPD), employing ethanol as a solvent under alternating current (AC) conditions. The deposition conditions for the nano HAP layer were set at 60 volts for 6 minutes with a suspension concentration of 3 g/L, while for nano YSZ, they were 40 volts for 4 minutes with a concentration of 1 g/L, all conducted at room temperature. Notably, the HAP-coated Ti-6Al-4V alloy demonstrated superior resistance to corrosion when compared to the uncoated substrate in a simulated body fluid solution. These enhancements were substantiated by a shift towards a more noble corrosion potential and a reduced corrosion current density [59].

In this investigative undertaking, hydroxyapatite (HA) coatings were synthesized with substitutions of magnesium (Mg), zinc (Zn), and silicon (Si) employing microwave irradiation. The outcomes revealed the production of uniform coatings with a consistent thickness within the range of 50 to 70 μm. Among these coatings, the Mg-HA coating demonstrated the least bacterial adhesion at 30 minutes and 2 hours, while the Si-HA coating exhibited minimal adhesion at the 6-hour mark. The electrophoretic deposition (EPD) technique proved to be highly effective in achieving uniform coatings on biocompatible metal implants. Notably, ionic-substituted HA emerged as a promising alternative coating material due to its reduced susceptibility to bacterial adhesion compared to conventional HA coatings [60].

To enhance the mechanical characteristics of hydroxy-apatite (HA), a composite incorporating additional bio ceramic materials like MgO, TiO_2, SiO_2, and ZnO was introduced. These materials are notable for their remarkable mechanical strength, fracture resilience, and resistance to wear, corrosion, and deterioration when subjected to physiological fluids. This approach holds significant promise for a wide array of applications within the realm of biomaterials [61].

2.7 Biocompatible polymeric or plastic coating

Biocompatible polymeric or plastic coating materials are crucial in medical and industrial applications, especially those involving interactions with biological tissues or environments. These materials must meet stringent requirements for biocompatibility, durability, and performance. Below is a detailed overview of some commonly used biocompatible polymers: [50,51,62].

1. Polytetrafluoroethylene (PTFE): The properties of polytetrafluoroethylene (PTFE) Chemical Resistance: PTFE exhibits exceptional resistance to nearly every type of chemical, rendering it perfect for settings where chemical deterioration or corrosion poses a risk. & Low Friction: Its low friction coefficient lessens wear and tear, which is important for medical device moving components. Thermostatic Stability: PTFE is appropriate for sterilizable devices since it can tolerate a broad variety of temperatures without deteriorating. Applications: Guidewires and catheters: These devices' PTFE coatings provide for easy passage through blood arteries with the least amount of tissue irritability and friction. & Implants: Because PTFE is inert, it is utilized in implants that need to be stable over the long term and resistant to body fluids.

2. Polyethylene Glycol (PEG): The properties of Hydrophilicity PEG have a high solubility in water, which aids in lowering immunological responses by preventing protein adsorption and cell adherence on surfaces. Non-toxicity: PEG is safe to employ in a variety of biological applications since it is neither poisonous nor immunogenic. Flexible Structure: PEG's flexibility makes it simple to coat a variety of substrates, such as medical device surfaces and nanoparticles. and How Drug Delivery Systems Are Used: PEGylation, or coating with PEG, is a technique used to decrease immunogenicity by increasing a drug's solubility and length of blood circulation. Implants: PEG coatings are applied to implants to provide “stealth” surfaces that inhibit immune system activation and hinder protein adsorption.

3. Polyurethane: The Elasticity and Flexibility of Polyurethane: Polyurethane is a great material for applications requiring flexibility and movement because it can simulate the elasticity of tissues. & Blood Compatibility: When in contact with blood, polyurethane’s high hemocompatibility lowers the chance of thrombosis. The durability of the material is crucial for long-term implants as it can withstand deterioration within the body. The Uses of Vascular Grafts: Because polyurethane is flexible and compatible with blood, it is utilized to create artificial blood vessels. Heart valves and catheters: Due to their biocompatibility and robustness, they are appropriate for long-term use in devices that come into contact with blood.

4. Polylactic Acid (PLA): PLA possesses several desirable properties: it is a biodegradable polymer that the body naturally breaks down into lactic acid; it also has good mechanical strength that can be customized by varying its molecular weight; and it can be processed into a variety of shapes and forms, such as films, fibers, and 3D-printed structures. Utilizing Polylactic Acid for Applications Sutures that spontaneously break down in the body and don’t need to be removed are called resorbable sutures, or PLA. PLA can be utilized to create biodegradable drug delivery systems that release drugs gradually as they break down. Tissue Engineering Scaffolds: PLA scaffolds promote tissue regeneration and progressively break down as new tissue forms.

5. Polycaprolactone (PCL): The Real Estate is Biodegradability: PCL is appropriate for long-term use because it breaks down gradually in the body. Blend Compatibility: PCL mixes easily with other polymers to enable property modification and Low Melting Point: PCL is easily processed and fabricated into a variety of forms due to its low melting point. The Uses of Long-Term Implants: Polycyclic Aromatic Linoleic Acid (PCL) is utilized in scaffolds for tissue engineering, where its slow degradation rate corresponds with the rate of tissue growth, and in devices that need a slow degradation rate, like some drug delivery systems.

6. Silicone: Qualities are Biostability: Silicone exhibits remarkable stability in biological settings, withstanding deterioration and retaining its characteristics over an extended period. Flexibility: Because of its softness and flexibility, implants and other devices that must adapt to the body can feel comfortable using it. Thermal and Chemical Stability: Silicone is resistant to several substances and maintains its stability over a wide temperature range. The applications are Artificial limbs and facial prostheses are made of silicone because of its realistic texture, elasticity, and Medical tubing, catheters, and implants are prominent applications for it, as they require flexibility and long-term biocompatibility.

7. Polydimethylsiloxane (PDMS) : The properties of elasticity of polydimethylsiloxane (PDMS) allow it to regain its original shape after deformation, which is advantageous in dynamic applications. Transparency: It is appropriate for optical devices and microfluidic applications due to its optical transparency. The Biocompatibility: Because PDMS is non-toxic and inert, it is acceptable for use in a variety of medical applications. Microfluidic Devices: PDMS’s transparency and ease of manufacture make it a popular choice for lab-on-a-chip systems. Contact Lenses: It can be used in contact lenses due to its oxygen permeability and biocompatibility. Wound Dressings: When flexibility and gas permeability are needed, PDMS is employed in wound dressings.

8. Polyethylene (PE): Chemical Inertness Properties: PE does not react with biological fluids or tissues and possesses a high degree of chemical resistance. Because Biostability does not degrade within the body, it is ideal for long-term implants. PE exhibits exceptional resistance to wear, making it a valuable material for joint replacement applications. How Joint Replacements Are employed: PE is employed in the bearing surfaces of artificial joints because it is wear resistant and compatible with biological tissues and catheters. Because of its flexibility and inertness, PE is suitable for use in medical tubing applications such as catheter coatings.

9. Polyetheretherketone (PEEK): high mechanical strength: PEEK is renowned for having remarkable mechanical qualities, such as stiffness and strength, that are on par with metals. Biocompatibility: When implanted in the body, PEEK is inert and does not result in negative reactions. PEEK is stable in moist conditions, including the human body, since it is resistant to hydrolysis.

PEEK's strength and biocompatibility make it an excellent material for use in spinal cages and other orthopedic implants. PEEK is utilized in dental implants, orthopaedic devices, and frameworks as a metal-free substitute. PEEK is an excellent substitute for metal in a variety of orthopedic applications due to its strength and low weight.

10. Polyglycolic Acid (PGA) : PGA's biodegradability breaks down into glycolic acid, which the body naturally metabolizes, more quickly than PLA's biodegradability. High Tensile Strength of PGA: PGA has exceptional tensile strength, which makes it appropriate for uses needing transient structural support and In medical applications, the controlled breakdown rate of PGA can be adjusted to correspond with the healing process. The programs are Resorbable sutures made of PGA are frequently employed in tissue engineering applications. These sutures dissolve as the tissue ages and are absorbed by the body after a certain amount of time, removing the need for suture removal. The Bone Fixation Devices: Resorbable screws and pins that offer short-term stability while the bone heals are made of PGA, which eventually dissolves.

2.8 Challenges and Considerations [66].

Sterilization: Biocompatible coatings must withstand sterilization processes such as autoclaving, gamma radiation, or ethylene oxide without degrading or losing their properties.

Adhesion: The adhesion of the coating to the underlying substrate is crucial for long-term performance. Poor adhesion can lead to delamination and failure of the device.

Degradation Products: For biodegradable polymers, the by-products of degradation must be non-toxic and safely metabolized or excreted by the body.

Surface Properties: Surface properties like roughness, hydrophilicity, and charge can influence protein adsorption, cell adhesion, and overall biocompatibility.

3. Discussion:

3.1 Comparison of Mechanical Properties of Biomaterials in Medical Applications

According to Table 1, the mechanical properties of biomaterials play a crucial role in their suitability for various medical applications. Stainless steel, with its high Young's modulus of 200 GPa, impressive tensile strength ranging from 586 to 1351 MPa, and a hardness of 190 HV, shines in applications such as joint replacements, dental implants, and orthopaedic fixtures. Titanium and its alloys, known for their Young's modulus of 110 GPa and a robust tensile strength of 760 MPa, find extensive use in cochlear and joint replacements, dental implants, as well as cardiac devices.

Zirconia exhibits a Young's modulus between 150 and 200 GPa, tensile strength ranging from 200 to 500 MPa, and a remarkable hardness of 1000 to 3000 HV, making it

Table 1. Utilizations of Biomaterials and Their Mechanical Characteristics [62]

Biomaterials	Applications	Mechanical properties		
		Young's modulus (Gap)	Tensile strength	Hardness (H_v)
Stainless steel	Substitutions for joints (hip and knee), bone plates used to fix fractures, dental implants, heart valves, spinal implants, hip nails, and shoulder prostheses	200	586–1351	190
Titanium and its alloys	Replacements for the cochlear system, substitutes for bones and joints, dental implants, sutures for orthodontic implants, artificial heart valves, and devices like pacemakers.	110	760	-
Zirconia	Replacements for hip, knee, teeth tendons, ligaments, repairs for periodontal disease, bone fillers.	150-200	200-500	1000-3000
Magnesium	Magnesium and its alloys, when used as materials for biodegradable metallic implants, offer significant benefits. These include outstanding biodegradability, compatibility with biological systems, and appropriate mechanical properties.	0.215 to 0.265	240-225	1091-650

a top choice for hip and knee replacements, dental procedures, and bone repairs. Meanwhile, magnesium, characterized by a Young's modulus of 0.215 to 0.265 GPa, tensile strength in the range of 240 to 225 MPa, and hardness values spanning from 1091 to 650 HV, stands out as a biodegradable implant material with biocompatible and suitable mechanical properties. It is crucial to grasp these mechanical characteristics when choosing biomaterials customized for specific medical purposes. This ensures the effectiveness and safety of biomedical applications.

Beyond their individual merits, a common theme emerges when examining these biomaterials: the pivotal role of mechanical properties in determining their suitability for medical purposes. It is clear that each material's distinct blend of Young's modulus, tensile strength, and hardness aligns them with specific medical functions.

Stainless steel, boasting high tensile strength, excels in load-bearing applications, while titanium's biocompatibility and strength make it a valuable choice for implants. Zirconia, known for its exceptional hardness and biocompatibility, finds its niche in dental and orthopedic applications. Moreover, magnesium's biodegradability and biocompatibility position it as a promising candidate for temporary implants. Together, these insights underscore the fundamental significance of mechanical properties in both crafting and choosing biomaterials for an array of medical applications, ensuring their success in clinical settings.

3.2 Comparative Analysis of Orthopaedic Coating Technologies: Advantages and Considerations

Exploring coatings for stainless steel in orthopaedic applications has led to a range of noteworthy findings, each with its unique strengths and potential drawbacks. One pivotal technique that has emerged is electrophoretic deposition (EPD), offering enhanced corrosion resistance and improved bioactivity. It's important to note, though, that its application may require specialized equipment and expertise. Incorporating silicon carbide (SiC) into hydroxyapatite (HA) coatings and developing degradable antibacterial coatings have demonstrated significant benefits in terms of corrosion resistance and infection prevention. Nevertheless, the complexity involved in manufacturing and applying these coatings could present challenges. Composite coatings, which combine materials such as polyvinyl alcohol (PVA), chitosan, bioactive glass, and graphene oxide (GO), have yielded valuable insights into material performance, resulting in enhanced properties. However, producing these composite coatings may involve intricate processes [61].

Within the domain of titanium coatings, innovations in superhydrophobic composites have led to improved hydrophobicity and wear resistance. However, the inclusion of tungsten trioxide (WO_3) and Pd-Ni/TiO_2 coatings, although enhancing mechanical strength and corrosion resistance, may lead to increased production costs and complexity.

Zirconium-based coatings have made significant strides in corrosion resistance and antibacterial properties, particularly suitable for orthopaedic and dental implants. Nonetheless, challenges related to scalability and cost-effectiveness may arise. Magnesium coatings, particularly in nano-hydroxyapatite composites, offer the promise of enhanced mechanical properties and reduced degradation rates but may be best suited for specific implant types [62].

Various composite coatings incorporating hydroxyapatite, graphene oxide, talc, collagen, and multi-walled carbon nanotubes have demonstrated improved corrosion resistance, mechanical strength, and biocompatibility. However, these coatings may involve complex material handling and fabrication procedures. In conclusion, these findings represent substantial advancements in coating technologies, presenting an array of advantages and challenges that necessitate careful consideration in their application across orthopaedic, dental, corrosion protection, and wear-resistant contexts, ultimately enhancing the longevity and performance of diverse materials [63].

4. Conclusions

Metallic biomaterials play an indispensable role in the realm of modern medical devices. This review investigates into the forefront of research, encompassing areas such as composite coatings, corrosion resistance, porous structures, and adhesion, the key facets of controlling corrosion within the human body. Current endeavours are chiefly directed towards fine-tuning the selection of materials and perfecting techniques for modifying surfaces. The management of corrosion is of utmost significance, given its potential to trigger implant failure, which could, in turn, lead to severe repercussions such as toxicity and tissue damage.

Notably, the strategic design of porous structures has emerged as a pivotal factor in fostering essential cellular processes, including attachment, proliferation, and, consequently, the facilitation of new bone regeneration. The strength of adhesion intricately hinges upon factors like coating thickness and solvent retention, presenting opportunities for precise control via concentration adjustments and dip repetition.

The electrophoretic deposition (EPD) technique has undeniably showcased its capabilities in producing healthy bioactive composite coatings, holding particularly promising prospects in the context of orthopaedic uses. These composite coatings hold substantial potential for elevating both mechanical and biochemical properties when compared to pure HA coatings. Nonetheless, the field necessitates a comprehensive exploration of the ideal metal compounds or alloys to optimize implant performance. However, challenges continue to loom large in the domain of metal implants, ranging from concerns about corrosion resistance to issues surrounding ion release and biocompatibility. Significantly, the clinical trial phase remains a critical bottleneck in the development process. Encouragingly, substantial strides have been made, offering promising avenues for infection control and the establishment of suitable utilization conditions.

As we look to the future, my ongoing research endeavours will pivot towards a more focused examination of particle adhesion within the IBD technique and strategies to enhance corrosion resistance. In addition, I will research into various composite coating methods, incorporating polymer reinforcements such as zirconium, titanium oxide, and magnesium oxide.

This review may furnish invaluable insights for researchers and practitioners actively engaged in diverse aspects of bone implant design and fabrication. The development of composite coatings, including combinations of ceramics and polymers with metallic implants, holds immense potential for significantly augmenting their mechanical properties and, consequently, expanding their utility within the realm of biomedical applications.

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