Journal of Composites and Compounds 5 (2023) 1-6

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Journal of Composites and Compounds

Biocompatible coatings for composite medical implants: enhancing integration and performance

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ABSTRACT

Biocompatible coatings are vital in enriching the performance of composite materials used in medical implants and prosthetics. These coatings improve the interaction between implants and biological tissues, boosting integration and overall functionality. The article discusses three main types of coatings includes polymer coatings (flexible and easy to apply), ceramic coatings (providing hardness and corrosion resistance), and composite coatings (combining polymers and ceramics for enhanced properties). Various fusion techniques, such as spray coating, dip coating, and electrospinning, are employed to achieve optimal coating characteristics. The article also highlights the importance of surface and mechanical testing to assess coating stability. In biomedical applications, coatings like hydroxyapatite for bone integration and titanium-based coatings for wear resistance are critical. Despite advances, challenges remain in creating durable, customizable coatings for specific applications. Ongoing research purposes to develop responsive coatings with smart functionalities, offering potential progresses in medical implant performance.

ARTICLEINFORMATION

Article History:
Received August 23 2023
Received in Revised form November 29 2023
Accepted December 25 2023

Keywords:
Biocompatible Coatings
Composite Medical Implants
Ceramic Coatings
Composite Coatings

1. Introduction

The development of composite materials for biomedical applications, especially implants and prosthetics, requires biocompatible coatings [1]. By improving the interface between the implant and biological tissue, these coatings improve implant performance and defense against adverse reactions [2]. Biocompatible coatings are crucial for ensuring successful integration of composite medical implants with biological tissues and improving their performance [1]. A variety of coatings are available, addressing issues such as biocompatibility, osseointegration, and infection prevention. Medical implants are significantly more successful if their biocompatible coatings promote favorable cellular responses and minimize adverse immune reactions [3]. In order to develop biocompatible coatings, a variety of materials and techniques are used, each of which offers unique advantages. There are hydroxyapatite (HA) coatings, bioactive glasses, and polymer-based coatings, among others [1]. Coating technologies, such as surface modification techniques and composite coatings, have expanded the possibilities for improving implant performance in recent years [2]. The purpose of this article is to explore the various biocompatible coatings available for composite medical implants and to analyze their contributions to improving integration and functionality. The significance of these coatings, types of biocompatible materials used, and recent advances in coating technology will be discussed. Moreover, we will provide an overview of the current state and future directions of this critical biomedical engineering field by comparing various synthesis techniques, considering factors such as time and coating thickness range.

2. Types of coatings

Coatings can be arranged into several categories based on their composition and claim [4]. We focused on three significant types of coatings. First of all, Polymer coatings are organic materials that afford protective and ornamental surfaces. They are generally used due to their flexibility, ease of application, and superb performance characteristics [5]. Major types of polymer coatings include epoxy coatings [6]. They were identified for their resilient adhesive properties and chemical resistance. Epoxy coatings are commonly used in industrial tenders for defending purposes. They form a tough layer that can survive harsh environments but may vitiate under UV exposure [7]. In addition, polyurethane Coatings offer distinct resistance to scrape, corrosion, and enduring. They can be stated for several applications, including as primers or topcoats in automotive and engineering situations [8]. Furthermore, Acrylic Coatings valued for their clarity and UV also they often used in outdoor

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https://doi.org/10.61186/jcc.5.4.4

claims [9]. They provide good color maintenance and gloss but may have limited chemical resistance allied to other polymers [10]. Plus, Silicone Coatings provide exceptional temperature reliability and water resistance, making them suitable for automotive and electronic applications[11]. Meanwhile water-based latex coatings are general for household paints due to their ease of application and quick drying times[12].

On the other hand. Ceramic coatings consist of inorganic materials that present exclusive hardness, thermal stability, and chemical resistance. They are repeatedly used in high-performance applications where durability is critical [13]. Notable landscapes contain thermal barrier properties can withstand high temperatures without degrading, making them ideal for applications in aerospace and automotive productions[14]. Besides that, corrosion resistance shelter substrates from corrosion in harsh environments, spreading the lifespan of components. Further, the hardness of ceramic coatings makes them effective in dropping wear on mechanical parts, which is necessary in industrial machinery [15].

Composite coatings combine different materials to accomplish improved properties that neither material could provide alone. They offer a stability of performance characteristics tailored to comprehensive applications [16]. Composite coatings may mix polymers with ceramics or metals to develop adhesion, flexibility, and strength [17]. For example, Friedrich et al. [18] reported that a polymer matrix reinforced with ceramic particles can enhance wear resistance while maintaining suppleness. Meanwhile, the incorporation of materials allows for customization based on the desired features such as current conductivity, electrical insulation, or enhanced mechanical strength [19]. The percentage of papers selected for coating materials is shown in Fig. 1 Due to their superior tribological properties, Diamond like Carbon is the most commonly used coating material (61%) in artificial joints. The orthopedic industry is not well acquainted with Tantalum and Graphite like Carbon, but a few studies have demonstrated their potential for joint prostheses. Over 10 years of clinical experience have been accumulated by Titanium Nitride surface-coating technology.

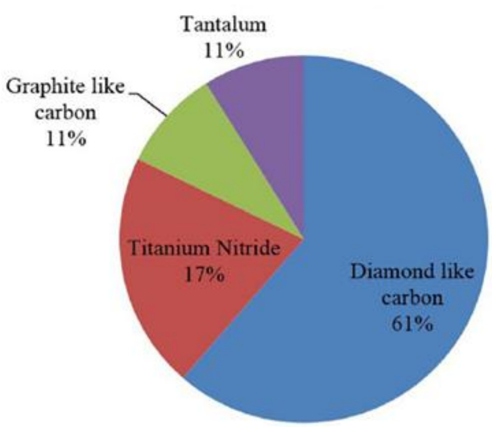

Fig. 1. Materials used for coatings [20].

3. Synthesis techniques

Coating techniques are necessary for concerning protective, functional, or decorative layers to various substrates. Among the frequent methods available, spray coating, dip coating, and electrospinning stand out due to their exclusive advantages and applications [21].

At first, spray coating involves atomizing a liquid coating material into fine droplets and projecting them onto a substrate surface [22]. This method can be performed using various spray methods, containing air spray, airless spray, and electrostatic spray. The choice of method depends on the desired coating thickness, uniformity, and material properties [23]. In addition, the coating material is arranged in a proper viscosity for atomization [22]. Also, the liquid is cracked into droplets using compressed air or mechanical means [24]. The droplets are directed toward the substrate, where they obey and form a continuous layer as the solvent evaporates [25]. Spray coating is usually used in automotive and aerospace industries for applying paints and protective coatings. It is also employed in manufacturing electronic components, where specific application of materials is crucial [26].

Thus, dip coating involves submerging a substrate into a liquid coating solution and then retreating it at a controlled speed [27]. The thickness of the coating can be adjusted by shifting the withdrawal speed and the viscosity of the result. The substrate is cleaned to ensure proper adhesion [28]. Furthermore, the substrate is dipped into the coating solution for an indicated time. The substrate is slowly pulled out of the solution, allowing excess material to drain off [29]. The coated substrate is dried to remove solvent and cure the coating[30]. Dip coating is commonly used for applying coatings to large surfaces or compound geometries, such as metal components in automotive applications or glassware in laboratory situations. It is also effective for creating uniform coatings on porous materials [11].

Also, electrospinning is a technique used to produce nanofibers from polymer solutions or melts by applying a high-voltage electric field. This process allows for the creation of very fine fibers with diameters in the nanometer range [31]. polymer solution or melt is prepared with appropriate absorption [33]. A syringe containing the polymer solution is allied to a high-voltage power supply [32]. When voltage is applied, the solution forms a charged jet that bounces as it travels toward a grounded collector, leading to fiber formation as the solvent evaporates. The fibers are collected on a substrate or rotating drum [33]. Electrospinning is used in various fields, including biomedical engineering for creating scaffolds for tissue engineering, filtration materials due to their high surface area-to-volume ratio, and protective clothing [34]. Table 1 compares various synthesis techniques for biocompatible coatings, focusing on time and coating thickness range. They can vary depending on specific parameters, equipment, and materials. Depending on the requirements of the application, the coating material, and the properties of the substrate, each technique has its own advantages and limitations.

4. Characterization of coatings

The characterization of coatings is crucial for understanding their performance, durability, and suitability for specific applications. This process involves evaluating surface properties and conducting mechanical testing to assess the coatings' effectiveness in various environments [35].

Surface properties expressively influence the performance of coatings, including union, corrosion resistance, and hydrophobicity [36]. Numerous analytical techniques are employed to characterize these properties. X-ray Photoelectron Spectroscopy is extensively used to investigate the elemental composition and chemical states of elements at the surface of coatings [37]. XPS provides qualitative and calculable information about the surface chemistry, which is vital for understanding how coatings interact with their environment [38]. Further, Atomic Force Microscopy offers high-resolution imaging of surface topography at the nanoscale [39]. AFM technique allows for the measurement of surface roughness and texture, which can affect adhesion and wear resistance [40]. In addition, Scanning Electron Microscopy provides thorough images of the coating surface morphology and can be used to analyze defects or irregularities that may affect performance [41].

Table 1

Comparison chart of biocompatible coating synthesis techniques.

Technique	Time	Coating Thickness Range (μm)	Advantages	References
Plasma Spraying	Fast (minutes)	30-200	High deposition rate, good for thick coatings	[42]
Sol-Gel	Slow (hours to days)	0.1-10	Easy to control composition, good for thin films	[43]
Electrochemical Deposition	Moderate (minutes to hours)	1-100	Good control over thickness and composition, cost-effective	[44]
Magnetron Sputtering	Moderate (hours)	0.1-10	High-quality films with good adhesion, dense coatings	[45]
Pulsed Laser Deposition	Fast (minutes)	0.01-10	High precision, good for complex geometries	[46]
Biomimetic Deposition	Very Slow (days to weeks)	1-30	Mimics natural processes, good for bioactive coatings	[47]
Electrophoretic Deposition	Fast (minutes)	1-100	Good for complex geometries, cost-effective	[48]

It is often used in conjunction with energy-dispersive X-ray spectroscopy (EDX) for compositional analysis. The other method is Contact Angle Measurement which assesses the wettability of a coating by measuring the contact angle formed by a droplet of liquid on its surface [50]. The contact angle provides intuitions into the hydrophobic or hydrophilic nature of the coating, influencing applications in biomedical strategies and anti-fogging surfaces. Meanwhile, Fourier Transform Infrared Spectroscopy is employed to find organic and inorganic compounds within coatings. It helps in characterizing functional groups present in polymeric coatings, which can affect their chemical constancy and communication with biological tissues [49]. Also, Mechanical testing is needed for appraising a coating's durability and performance under innumerable conditions. Numerous procedures are commonly used for hardness and elastic modulus of coatings at the nanoscale [50]. It provides valuable information about how a coating will perform under mechanical stress and its conflict to deformation[51]. Furthermore, Adhesion tests assess how well a coating adheres to its substrate [52]. Mutual methods hug tape tests, scratch tests, and pull-off tests, which help determine if the coating will remain intact through facility conditions. Moreover, Impact Resistance Testing assesses a coating's ability to withstand sudden armies or impacts without chipping or cracking [53]. Controlled impact tests simulate real-world conditions where coatings may be subjected to mechanical stress [53]. Also, techniques like salt spray testing evaluate how well a coating protects against corrosion in aggressive environments. This testing simulates long-term exposure to saltwater conditions to assess protective capabilities. Meanwhile these tests expose coatings to varying temperatures to determine their thermal stability and resistance to cracking or delamination under thermal stress [54].

5. Performance of coatings in biomedical applications

Coatings play a key role in enhancing the presentation of biomedical implants, particularly in orthopedic and dental applications. These coatings improve the biocompatibility, mechanical properties, and overall functionality of implants, addressing corporate challenges such as corrosion, wear, and biological interactions [55]. Fig. 2 provides a clear overview of the different coatings used in orthopedic and dental implants and their specific functions.

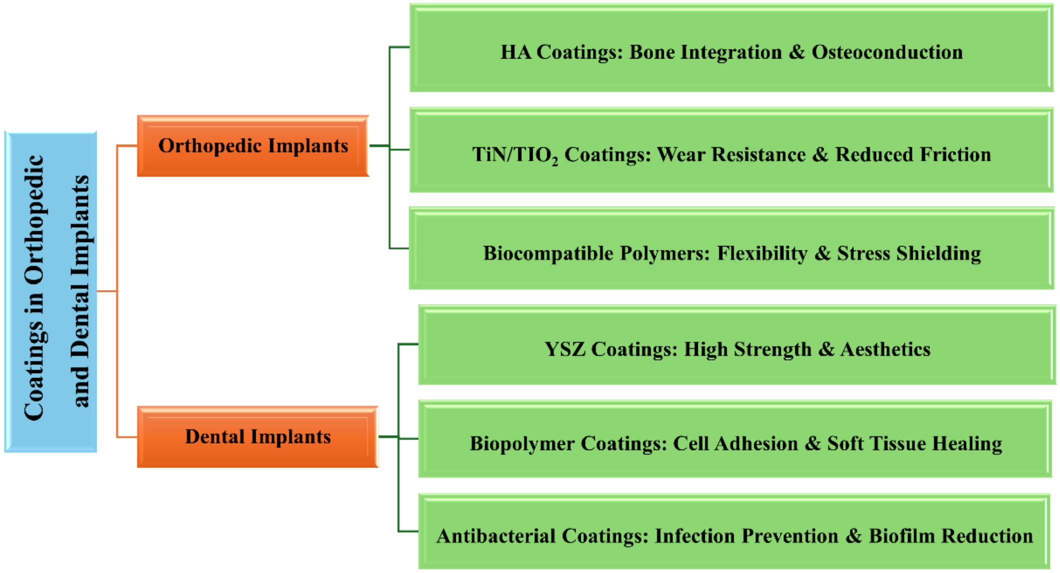

Fig. 2. Coatings in Orthopedic and Dental Implants.

5.1 Orthopedic implants

Orthopedic implants are designed to support or replace damaged bone structures [58]. The performance of these implants is heavily partial by their surface belongings, which can be superior through diverse coating techniques. Ceramic materials like hydroxyapatite (HA) are widely used due to their excellent osteoconductive properties, promoting bone integration and regeneration [59]. HA coatings facilitate the attachment and proliferation of osteoblasts, enhancing bone healing around the implant. Additionally, ceramic coatings provide corrosion resistance, crucial for long-term stability in the physiological environment [56]. Likewise, coatings such as titanium nitride (TiN) and titanium dioxide (TiO_2) improve wear resistance and reduce friction between the implant and surrounding tissues. These coatings also enhance biocompatibility by providing a more favorable surface for cellular interactions. Additionally Biocompatible polymers can be applied to orthopedic implants to improve flexibility and reduce stress shielding effects. These coatings can also be engineered to release bioactive compounds that promote tissue healing [57].

5.2 Dental implants

Dental implants require specific surface features to guarantee effective mixing with bone and soft tissues [58]. The following coating types are commonly utilized Zirconia Coatings which stabilized with yttria (YSZ) is increasingly popular for dental implants due to its high strength, wear resistance, and excellent aesthetic properties. YSZ coatings have shown improved hemocompatibility, promoting better contact with blood components. This is particularly helpful for implants subjected to dynamic loading conditions in the oral cavity. While biopolymers such as chitosan and collagen can be used as coatings to enhance cell adhesion and proliferation on dental implants. These materials support soft tissue healing around the implant site, which is critical for long-term success [59]. Besides, to moderate the risk of infection allied with dental implants, antibacterial coatings incorporating silver or other antimicrobial agents are active. These coatings help prevent biofilm formation on the implant surface, reducing the likelihood of peri-implantitis [60].

6. Challenges and future directions

Despite advancements in coating technologies, several challenges remain. Ensuring that coatings maintain their integrity over time under physiological conditions is crucial. Research is ongoing to develop more durable coatings that resist wear and corrosion while maintaining biocompatibility [1]. Secondly, The ability to modify coating assets for unambiguous applications is essential [61]. Future developments may focus on smart coatings that respond to environmental changes or release therapeutic agents in response to biological signals. Meanwhile, as new coating materials are developed, they must undergo rigorous testing to meet safety and efficacy standards before clinical application [62]. The ambition, is to explore the part of biocompatible coatings in ornamental the performance of medical implants. It introduces several types of coatings, synthesis techniques, and their evaluation methods. Additionally, it examines the impact of these coatings on the collaboration among implants and biological tissues, refining their durability in different environmental situations.

7. Conclusion and future directions

The development of biocompatible coatings for composite medical implants has become a critical area of research aimed at enhancing the integration and performance of these devices. Coatings such as hydroxyapatite, bioactive glasses, and advanced polymers have shown significant promise in improving osseointegration, reducing the risk of infection, and promoting overall implant functionality. As the demand for effective and long-lasting implants continues to rise, particularly in an aging population, the importance of these coatings cannot be overstated.

Future research should focus on exploring new materials such as graphene and diamond-like carbon coatings, which offer unique mechanical and chemical properties that could enhance the performance of medical implants. The trend towards personalized medicine suggests that coatings could be tailored to meet individual patient needs. Customizing coatings based on patient-specific factors may improve compatibility and reduce complications. The development of smart coatings that respond to environmental stimuli (e.g., pH changes, temperature variations) could revolutionize implant technology. These coatings could release therapeutic agents in response to specific biological signals, enhancing healing processes. The complexity of developing effective biocompatible coatings necessitates collaboration among materials scientists, biomedical engineers, clinicians, and regulatory bodies. Such interdisciplinary efforts will accelerate innovation and ensure that new technologies meet clinical needs. Furthermore, navigating the regulatory landscape for new coating technologies remains a challenge. Streamlining the approval process while ensuring safety and efficacy will be vital for bringing innovative solutions to market more quickly. Also, comprehensive long-term studies are essential to evaluate the performance of new coatings in real-world clinical settings. Gathering data on their effectiveness over time will provide valuable insights into their reliability and potential for widespread adoption. Overall, biocompatible coatings represent a promising frontier in the field of medical implants, with the potential to significantly enhance patient outcomes through improved integration, reduced infection rates, and increased durability. Continued research and innovation in this area will be crucial for addressing the evolving needs of healthcare providers and patients alike.

Authors' contribution

Zahra kheradmand: Investigation, Writing—Original Draft Preparation, Writing—Review and Editing, **Taha Mohammadi:** Writing—Original Draft Preparation, Writing—Review and Editing, **Grace Iyaloo Tukuna Mukete: :** Writing—Original Draft Preparation, Writing—Review and Editing.

Declaration of competing interest

The authors declare that there are no competing interests.

Data availability

The article describes no data used in the research.

Funding

None.

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