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Development of Bioactive Composite Coatings on 316L Stainless Steel by Electrophoretic Deposition for Orthopedic Applications

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Abstract

Surgical implants are being replaced by many alloys, including medical stainless steel (L316). These alloys have high specifications, such as high corrosion resistance, high biocompatibility, and desirable mechanical properties. However, they suffer from a fundamental problem: the release of nickel and chromium ions into body fluids, which will cause deformation of the surrounding tissue area. In this study, an electrophoretic deposition (EPD) coating method was used to deposit a composite coating system of inorganic nano bioceramic materials consisting of nanohydroxyapatite (HA), nano magnesium oxide (MgO), and nano zinc oxide (ZnO) On medical austenitic stainless steel alloy (316L) with the use of organic chitosan (CHT) as a coating binder to improve the bonding strength between the coating layer and the substrate. The coating serves two purposes: first, it acts as a barrier, and second, it provides a suitable environment with porosity similar to that of bone, allowing the surrounding tissue to grow. This technology operates at room temperature and does not undergo phase transformation. The conditions used were voltage, time and concentration (20,40,60) V, (2,4,6) min, and (4,7,10) g/L respectively. The Taguchi method was used to select the optimum conditions for the precipitation process and design experiments for the selected variables (voltage, time and concentration). Using these optimum conditions, three types of composite coating were applied. The influence of these factors on coating thickness, surface roughness, adhesion, wettability, resulting microstructure, coating homogeneity, corrosion resistance, and antibacterial properties were investigated. Numerous tests were conducted after the coating process was completed. Optical microscopy and scanning electron microscopy (SEM) equipped with energy dispersive spectrometry (EDS) were used to analyze the elemental type and quantity. SEM was used to examine the composition of the coating layer deposited on the surface, as well as the cross-section of the coating. Atomic force microscopy (AFM) was used to characterize the surface morphology, to

evaluate the biological properties of the single and composite coating layers. The analyzed coatings were found to be crack-free, continuous, and homogeneous, as were the coatings. It was also observed that electro-deposition coatings preserve the phases formed before and after the coating process remain preserved, indicating that no phase transformation occurs during the coating procedure. This is considered one of the key advantages of this method. The adhesion test results between the coating layers of hydroxyapatite, zinc oxide and magnesium oxide with the base metal were (48 N, 50N, 53N) respectively, which were evaluated using the (scratch test) method. Furthermore, contact angle measurements showed that the coating surfaces transformed from a hydrophilic (base metal) property of 73.818° to a superhydrophilic (composite coating) of 9.78° . The results showed a decrease in corrosion rates from 4.386×10^{-1} mils per year for 316L stainless steel to 1.417×10^{-2} mils per year for MgO and 1.222×10^{-3} mils per year for MgO.

Chapter One

Introduction

1.1. Overview

Bone replacement surgery has been more popular among people of all ages in recent years. The human body is capable of self-repair following injury to damaged tissues. Loss of bone and function in neighboring tissues occur when an injury to the tissue or bone is too big to heal. If that's the case, new different materials can be used to rebuild the bone [1] One approach that is quite versatile is electrophoretic deposition (EPD). There are several shown benefits to using the EPD approach, such as advanced materials, thin coatings, nanostructures, and manufacture functionally graded materials (FGM) [2] A small quantity of starting material(s), minimal equipment cost, and easy-to-design apparatus is all necessary for EPD. Standard electrophoresis devices typically use a two-electrode cell and operate at an ambient temperature to perform EPD. The use of environmentally friendly materials or the need for specific measures are common in many processing methods involving EPD. However, It is important to properly coordinate these four elements in order to achieve a good coating selecting high materials with care, knowing all the principles to regulate the phenomena, designing the system correctly, and having a firm grasp on processing parameters (both dependent and independent) are all essential [3]. All these aspects can be controlled using theoretical and experimental expertise. Enzymes, bacteria, and cells are examples of biological fields that can benefit from EPD's advanced applications. Extensive research is being conducted by researchers from many universities and specialized institutions worldwide to create and improve various EPD coatings [4].

Electrophoresis-induced particle deposition (EPD) is an established method for selectively depositing charged particles from a stable-state colloidal solution in response to a direct current. The basic idea behind this approach is a two-step process where the movement of charged particles through a solvent liquid is the initial stage. This process is best carried out with an applied electric field (electrophoresis) present. The next stage involves the deposition of particles onto the electrode in the form of a coagulant [5]

In orthopedic and dental implant applications, 316L stainless steel is the most dependable substrate. 316L stainless steel is a popular choice for EPD coatings due to its intriguing features, which include excellent chemical, physical, biological, and mechanical qualities. However, stainless steel implants are prone to localized in vivo deterioration, which can lead to discomfort if left exposed for an extended length of time [6,7]. A localized corrosion phenomenon known as element ion release from stainless steel (Fe^{+2} , Cr^{+3} , and Ni^{+2}) is the primary source of this phenomenon. This occurs as a result of the implant interacting with the body's unpleasant fluid. The end outcome is a dose-dependent disruption of osteoblastic human bone cell proliferation and differentiation [8]. Furthermore, enough bioactivity is lacking in metals and alloys to investigate osteointegration, corrosion resistance, biocompatibility, and antibacterial rate. Another drawback of metals as a biomaterial is that their ion release into the body and encapsulation by fibrous tissues cannot be regulated. This can cause the implant to migrate, loosen, and undergo micromovements [9]. Consequently, these materials have to be modified in order for them to be appropriate as implants or as bioactive coatings for metallic implants in order to alleviate these difficulties. Inducing osteointegration and

reducing the discharge of undesirable metallic ions through the coating barrier effect are both dependent on this [10]. Plasma spraying, sol-gel, electrophoretic deposition, and other coating techniques are utilized to modify the surface characteristics of metallic implants. Since it was among the most efficient and effective ways to create useful materials and tools, the EPD process was both fascinating and significant. Low prices, quick adjustments, short times, simple equipment, as well as the final piece's thick particle packing and many applications characterize them. In the bio-ceramic coatings, hydroxyapatite (HA) is fundamental because its structure is similar to that of bone. Its exceptional bioactivity and compatibility with stainless steel make it ideal for a wide range of biomedical and medical uses. Among the most important compounds derived from calcium phosphate, stoichiometric hydroxyapatite ($\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2$) is found in the human body. In dentistry and orthopedics, among other biological fields, they have seen substantial use. Hydroxyapatite ceramic's greatest strength is its remarkable biocompatibility and osteoconductive, which it shares chemically with minerals. However, HA is not suitable for use in severe implant bearing contacts due to its poor fracture toughness and apparent brittleness [11,12]. Bioactive zinc oxide (ZnO) is another bio ceramic material that shows promise as a coating for stainless steel 316L. When added to HA composites in varying concentrations, it boosts bone production, enhances bioactivity, and exhibits antimicrobial activity. Biomedical uses for ZnO coating include improved osseointegration and enhanced corrosion resistance in stainless steel. Coating the alloy with ZnO makes it more biocompatible and increases its mechanical stability, making it an ideal material for use in plants and other medical devices. Finally, due to its

beneficial properties in biomedical domains, magnesium oxide (MgO) is increasingly being utilized as a bio ceramic coating material. By making implants more biologically active and mechanically stable, it encourages bone formation and integration. Applying MgO coatings on biodegradable magnesium alloys used in orthopedic implants improves their corrosion resistance and biocompatibility[13]. Additionally, MgO can release magnesium ions, which aids in the growth of osteoblasts and speeds up the healing process. Biomedical implants and medication delivery have made use of chitosan, a naturally occurring cationic polysaccharide with numerous beneficial characteristics, such as the capacity to eliminate germs, biocompatibility, and enhanced mechanical and other attributes [14]. One of the many biomedical applications of chitosan is as a coating material to alter the surface of orthopedic implants, because it has many physicochemical properties with the extracellular matrix found in articular cartilage and bone. It has several desirable properties, including being biocompatible, non-toxic, biodegradable, antibacterial, and chemically tolerant [2,15] .

1.2 Aim of the Work

1. To achieve uniformly coated surfaces that are both wettable, bondable, and morphologically accurate using EPD technique using a mix of biopolymer material (chitosan) and bio ceramic materials (both bioactive and bioinert).
2. The goal of employing EPD is to create new organic-inorganic composite coatings that are bioactive, ultimately used as bone replacements.

3. Creating biocompatible multi-property coating layers with excellent mechanical characteristics.
4. learning how different types of composite coating, both single and composite, react biologically.
5. Determining if the coating can create a surface layer of hydroxyapatite by testing its bioactivity, an additional layer that will give a surface that is osteoconductive, allowing bone to adhere this proves that the coating has bioactive properties.

1.3 Organization of the Study

This research is structured into five chapters and is organized as follows:

Chapter One presents the introduction and objectives of the current study.

Chapter Two Discusses the EPD method (including its fundamentals, influencing mechanisms and factors), provides an introduction to the biomaterials field, and concludes with a literature review.

Chapter three: include the materials which are used, Taguchi approach for optimizing the experiments and work procedure.

Chapter four: including Results and discussions.

Finally, the important conclusions and Recommendation suggestions for future studies are listed in **chapter five**.