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Surface Engineering of Dental Implants: Techniques, Mechanisms, and Clinical Considerations

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ABSTRACT

Dental implants have emerged as one of the most effective and widely accepted solutions for replacing missing natural teeth in modern dentistry. The long-term success or potential failure of dental implants is influenced by a range of local and systemic factors. Among these, the surface characteristics of the implant play a pivotal role in the initial biological response following implantation. In particular, surface roughness has garnered significant interest in recent years due to its ability to enhance the interaction between the implant and the surrounding bone tissue. To promote faster and more effective osseointegration, the direct structural and functional connection between living bone and the surface of the implant, numerous surface modification techniques have been explored. These include mechanical, chemical, and physical treatments, often utilizing various materials designed to improve biocompatibility and promote early bone healing. While a growing body of research suggests that such surface treatments can significantly accelerate healing, particularly in the initial stages following implant placement, clinical decision-making must still be guided by both the available scientific evidence and the specific needs of each patient case. This review article aims to synthesize current knowledge regarding the surface treatment of dental implants. By critically analyzing findings from various experimental and clinical studies, it provides insights into the advantages and limitations of different surface modification techniques currently in use. The goal is to assist clinicians and researchers in selecting appropriate implant systems based on evidence-based outcomes and clinical applicability.

1. Introduction

Dental implants have become a highly predictable and widely accepted modality for the rehabilitation of partially or completely edentulous patients [1-3]. Their increasing popularity is attributed to several advantages over conventional prosthetic options. Unlike removable or tooth-supported prostheses, implants provide independent support and

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retention for both fixed and removable restorations, thereby reducing the functional load on adjacent natural teeth and surrounding oral structures. Additional benefits include the preservation of alveolar bone, avoidance of damage to adjacent teeth, long-term durability, improved masticatory efficiency, and enhanced phonetics. These advantages have made dental implants a preferred treatment choice in modern restorative and prosthetic dentistry [4].

The functional success of dental implants depends on their ability to achieve and maintain osseointegration, a direct structural and functional connection between living bone and the implant surface without the interposition of soft tissue. Achieving successful osseointegration, however, is influenced by multiple factors. These include the biocompatibility of the implant material, the quality and volume of the host bone, the surgical and loading protocols used, and various systemic and local health conditions of the patient. Among these, the surface characteristics of the implant, particularly its topography and chemical composition, play a critical role in the early biological response and long-term stability of the implant [5].

Recent advances in implant technology have focused on modifying surface properties to improve the biological response and expedite the osseointegration process. Surface roughness, in particular, has emerged as a key determinant in enhancing the mechanical interlocking between the implant and bone tissue. Numerous studies have demonstrated that implants with moderately rough surfaces show superior bone integration compared to those with smooth surfaces. A wide range of surface modification techniques has been developed to enhance the topographical, chemical, and biological properties of titanium implants. These methods aim to improve cell adhesion, proliferation, and differentiation at the bone-implant interface [6]. Figure 1 illustrates the classification of surface modification techniques for dental implants into three main categories: additive processes, subtractive processes, and manufacturing techniques. Each category encompasses specific methods aimed at enhancing implant surface properties to improve osseointegration and clinical outcomes [7].

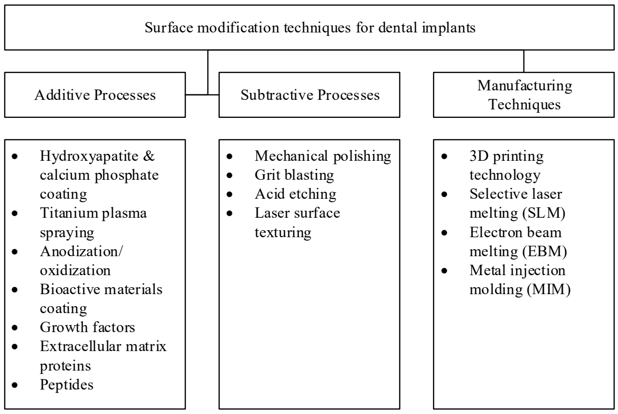

Figure 1. Surface modification techniques of dental implants categorized by additive, subtractive, and manufacturing processes.

The purpose of this review is to present a comprehensive overview of current surface treatment methods employed in dental implants. Beginning with the fundamental materials used in implant manufacturing, this paper examines various surface modification strategies designed to promote osseointegration and improve clinical outcomes.

2. Implant Biomaterials

Historically, early dental implants were fabricated from materials such as porcelain, gold, aluminum, platinum, and silver. Although these were initially explored for tooth replacement, their use was discontinued due to the development of inflammatory reactions and the formation of fibrous tissue at the implant site, which compromised their clinical performance.

Today, commercially pure titanium (cp-Ti) remains the gold standard in dental implantology [8]. While variations in survival rates are occasionally reported, potentially due to multifactorial causes, titanium continues to be preferred because of its exceptional biocompatibility. Its widespread use across numerous medical applications is a testament to its safety and effectiveness. Beyond biocompatibility, titanium offers several desirable properties including chemical inertness, corrosion resistance, non-allergenicity, cost-effectiveness, ease of protein adsorption, and support for cellular adhesion, proliferation, and differentiation [9].

Titanium naturally forms an oxide layer, and the combination of oxygen with titanium creates commercially pure titanium alloys. For surgical-grade implants, the oxygen content must be controlled to remain below 0.5%, in accordance with the British Standards specifications. Titanium exhibits allotropic transformation, shifting from its alpha phase (hexagonal close-packed structure) to the beta phase (body-centered cubic structure) at temperatures above 883°C. Elements such as oxygen, carbon, and nitrogen act as alpha-phase stabilizers, whereas molybdenum, niobium, and vanadium stabilize the beta phase [10].

Driven by the demand for tooth-colored, aesthetically pleasing alternatives, ceramic biomaterials have also been introduced in implant dentistry. Ceramics offer high biocompatibility, excellent compressive strength, and modifiability for surface treatments to enhance osseointegration. However, their inherent brittleness and low tolerance for tensile forces generated during occlusion limit their mechanical resilience. Among ceramics, aluminum oxide (Al_2O_3) and zirconia (ZrO_2) have demonstrated significant biostability. While alumina provides superior surface wettability, zirconia is advantageous due to its lower plaque accumulation and greater mechanical strength. Despite these benefits, Al_2O_3 implants were withdrawn from the market because of suboptimal survival rates, whereas zirconia remains a promising option, even under high occlusal loads. Another notable innovation is bioglass, a bioactive ceramic composed primarily of SiO_2, CaO, Na_2O, P_2O_5, and MgO. Bioglass promotes direct bone formation by stimulating cellular activity at the implant interface [11].

Researchers at the NRC Industrial Materials Institute in Canada developed an innovative material known as titanium foam, created by combining titanium powder with a polymer and a foaming agent. This material has a porous structure, which increases the implant's surface area and promotes osseointegration while also reducing surgical invasiveness. Roxolid®, a commercial alloy of titanium and zirconium, has been introduced to provide enhanced mechanical strength and improved stability, particularly in narrow-diameter implants [12].

With continuous advancements, a variety of techniques have been developed to modify the surface chemistry and topography of dental implants. Numerous studies have confirmed that roughened surfaces significantly increase bone-to-implant contact compared to smoother surfaces. These modifications can be broadly classified into two categories: Additive techniques, which involve depositing materials onto the implant surface to create protrusions or textured layers. Examples include titanium plasma spraying, hydroxyapatite (HA) and calcium phosphate (CaP) coatings, and ion beam deposition. Subtractive techniques, which involve removing material to create surface depressions. Common methods include sandblasting with aluminum oxide, acid etching, a combination of machining and etching, and electropolishing. Such surface treatments are aimed at improving early-stage biological integration and ensuring long-term clinical success of dental implants [7].

3. Titanium Plasma Spray and Hydroxyapatite Coating

The technique of roughening titanium implant surfaces using titanium plasma spray (TPS) was introduced approximately 35 years ago. Initially described in orthopedic applications by Hahn and Palich in the 1970s, the microporous nature of plasma-sprayed surfaces was later adopted for dental implants by Schroeder and colleagues. The process involves heating titanium to a plasma state and spraying it onto the implant surface. This creates surface irregularities, specifically pores ranging from 30 to 50 µm in depth, which significantly enhance microretention by increasing surface roughness. Following this treatment, the surface area of a titanium implant can become approximately three times greater than that of a traditionally machined implant [13].

In a comparative study by Klaus Gotfredson and Ulf Karlsson, machined implants were evaluated against titanium dioxide (TiO_2)-blasted implants over a five-year period. The results showed no statistically significant differences in implant failure rates or marginal bone loss between the two surface types. However, a multicenter longitudinal study conducted by William Becker in 2000 revealed that implants treated with plasma spray demonstrated notable bone loss between the time of loading and the 2–3 year follow-up period. The long-term clinical implications of this bone loss remain uncertain and warrant further investigation [14].

An alternative surface modification technique is hydroxyapatite (HA) plasma spraying, an industrial process designed to enhance the bioactivity of implant surfaces. In this method, HA is heated to extremely high temperatures (approximately 15,000 to 20,000 K) using a plasma flame, and then applied to the implant surface under inert atmospheric conditions. The resulting HA coating typically ranges in thickness from 50 to 200 µm, with a surface roughness between 7 and 24 µm [15].

Hydroxyapatite, due to its chemical similarity to bone mineral, demonstrates excellent osseoconductive properties. It forms a bioactive, osteophilic surface that supports rapid bone formation, particularly beneficial during the early healing phase. This makes HA-coated implants especially suitable for clinical scenarios requiring accelerated integration, such as immediate implant placement or in sites with compromised bone quality [15].

In vitro studies have shown that HA surfaces support significantly higher adhesion of human osteoblasts compared to uncoated titanium surfaces, indicating superior cellular compatibility. Supporting this, Klaus Gotfredson conducted a preclinical study in rabbits to compare the histomorphometric and biomechanical performance of TiO_2-blasted implants with and without HA coating. After 13 weeks, implants with HA coatings exhibited greater bone-to-implant contact and a higher proportion of mature lamellar bone in the surrounding cortical bone than their uncoated counterparts [14].

4. Grit Blasting

Grit blasting is a mechanical surface modification technique that involves propelling high-velocity abrasive particles onto the implant surface using compressed air. This bombardment creates varying degrees of surface roughness, depending on the size and nature of the abrasive particles used. Smaller particles, such as alumina with diameters between 25–75 µm, typically produce a mean surface roughness in the range of 0.5–1.5 µm. In contrast, larger particles ranging from 200–600 µm can generate significantly rougher surfaces, with roughness values between 2–6 µm [16].

Several operational parameters influence the final surface topography, including blasting pressure, duration, and the distance between the nozzle and the implant surface. The selection of blasting material is critical, it must be chemically inert, biocompatible, and should not interfere with the osseointegration process of the titanium implant [17]. A variety of ceramic materials have been employed for this purpose, including alumina, glass, silica, and titanium dioxide. However, a major concern with grit blasting is the potential embedding of residual blasting particles into the implant surface. These remnants may not be completely removed during standard cleaning procedures, posing a risk of adverse biological responses and impaired osseointegration.

To address this issue, post-blasting surface treatments, such as chemical etching, are often applied to eliminate embedded particles. However, these additional processes can partially reduce the surface roughness initially created by blasting. For this reason, the use of biocompatible blasting materials is strongly recommended to minimize the risk of negative interactions while maintaining desirable surface features [6]. Despite the widespread use of grit blasting, there is limited data available regarding the detailed composition and thickness of the oxide layers formed on blasted titanium surfaces. Nevertheless, in a clinical study conducted by Rasmussen, implants treated with titanium dioxide (TiO_2) blasting demonstrated reliable long-term support for fixed prostheses in both the maxillary and mandibular arches, indicating the clinical viability of this surface treatment approach [18].

5. Chemical Surface Treatments: Acid and Alkaline Etching

Chemical etching techniques are commonly employed to modify the surface of titanium dental implants, improving their bioactivity and enhancing osseointegration. Two prominent approaches include acid etching and alkaline etching, both of which alter surface morphology and chemistry to promote favorable biological responses. Acid etching involves the use of strong acids to clean the implant surface while producing a uniformly roughened texture at the microscale. Commonly used acid solutions for treating titanium and its alloys include mixtures containing 10–30% nitric acid (HNO_3, 69% mass concentration) and 1–3% hydrofluoric acid (HF, 60% mass concentration) diluted in distilled water. Another frequently applied combination is equal volumes (100 mL each) of hydrochloric acid (HCl, 18% mass) and sulfuric acid (H_2SO_4, 48% mass). These treatments typically result in the formation of a thin oxide layer on the implant surface—generally less than 10 nanometers thick—which gradually thickens over time when exposed to air, increasing from approximately 3 nm to 6 nm over a 400-day period [6].

A more advanced technique known as dual acid etching involves immersing titanium implants in a heated mixture of concentrated HCl and H_2SO_4 at temperatures above 100 °C for several minutes. This method produces a microtextured surface that significantly enhances early bone integration. Dual-etched surfaces facilitate the rapid attachment of fibrin and osteogenic cells, thereby promoting direct bone formation on the implant and supporting long-term clinical stability over at least three years. In addition to acid treatments, fluoride etching has been introduced as a method to further stimulate osseointegration. This technique forms a titanium tetrafluoride (TiF_4) layer on the implant surface, embedding fluoride ions that not only create surface roughness but also enhance cellular activity and bone-implant bonding [18].

Alkaline etching, in contrast, utilizes basic solutions to achieve surface modification. Treating titanium with 4–5 M sodium hydroxide (NaOH) at 60 °C for 24 hours results in the formation of a sodium titanate gel layer approximately 1 µm thick. This layer is characterized by an irregular topography and significant open porosity, with a primary composition of titanium dioxide (TiO_2). Subsequent heat treatment can further refine the structure and composition of the surface layer, potentially improving its bioactivity. When alkaline treatment is applied after acid etching, the resulting surface exhibits enhanced porosity and roughness, which may further facilitate bone integration [19]. Together, acid and alkaline surface treatments play a critical role in improving the osseointegration potential of titanium implants by optimizing surface characteristics at the micro- and nanoscale levels [20].

6. Anodization

Anodization is an electrochemical surface modification technique used to enhance the properties of titanium implants. This process involves applying high voltage to titanium in strong acidic electrolytes such as phosphoric acid (H_3PO_4), nitric acid (HNO_3), sulfuric acid (H_2SO_4), or hydrofluoric acid (HF). As a result, a thick and crystalline oxide layer forms on the implant surface, often exceeding 1000 nanometers in thickness [20].

The outcome of the anodization process is influenced by several factors, including the type and concentration of acid used, the composition of the electrolyte, and the nature of the electric current applied. This treatment modifies the microstructure and crystallinity of the titanium oxide layer, improving its biological properties [6].

Studies have shown that anodized titanium surfaces elicit a stronger bone response compared to machined surfaces, as evidenced by superior results in both biomechanical and histomorphometric evaluations. Clinically, implants with anodized surfaces have demonstrated higher success rates than those with turned (machined) surfaces of comparable geometry [21].

Additionally, specialized forms of the process, such as spark anodization, can create rough and microporous surfaces when performed in sulfuric or phosphoric acid solutions, or their combinations, typically at voltages exceeding 100 V. Spark anodization can also be carried out using electrolytes containing calcium and phosphorus, further enhancing the bioactivity and osseointegration potential of the implant surface [22].

7. Laser Surface Treatments

Laser surface treatment presents a promising alternative to conventional implant modification techniques, offering the advantage of minimizing contamination risk. This method is non-contact, precise, and clean, allowing for superior control over surface configuration and texture without physically touching the implant surface [23]. Laser-treated implants, particularly when combined with acid etching, can achieve an average surface roughness of approximately 2.28 µm. Research indicates that such surface modifications promote enhanced bone formation around the implant, which may be linked to the formation of a titanium nitride (TiN) layer during the laser process. This layer potentially contributes to improved biocompatibility and osseointegration [24-26].

8. Calcium Phosphate Coatings

Calcium phosphate coatings represent a class of bio-inorganic materials commonly used to modify titanium implant surfaces for enhanced performance in bone-related biomedical applications. These coatings aim to improve osseointegration by mimicking the mineral component of natural bone. However, the influence of calcium phosphate's physicochemical properties and its degradation behavior on new bone formation and long-term implant stability remains a topic of ongoing research and some debate [9].

Following implantation, calcium phosphate compounds are gradually released from the coated surface into the surrounding body fluids. This release leads to supersaturation, promoting the precipitation of a biological apatite layer on the implant surface. This newly formed apatite facilitates the adhesion, proliferation, and differentiation of osteogenic cells, thereby supporting bone regeneration and healing [27].

Numerous studies have reported that implants with calcium phosphate coatings exhibit stronger bone fixation and improved long-term clinical outcomes compared to uncoated implants. Although hydroxyapatite (HA) coatings produced by plasma spraying have shown promising results, concerns related to coating stability and long-term performance have prompted the development of alternative deposition methods. These include sputter deposition, sol–gel techniques, thermal spraying, hot isostatic pressing, pulsed laser ablation, electrophoretic deposition, and biomimetic coating approaches, all aimed at improving coating uniformity, adhesion, and biological performance [15].

9. Nanosilver Coatings

The oral cavity harbors a diverse microbiome, including bacteria capable of initiating peri-implantitis, a leading cause of dental implant failure. To mitigate microbial colonization and enhance implant longevity, antimicrobial surface treatments have been developed. Among these, silver nanoparticles (AgNPs) have attracted considerable interest due to their potent and broad-spectrum antimicrobial properties [28].

AgNPs exert their antibacterial effects through multiple mechanisms, particularly against Gram-negative bacteria:

1. Nanoparticles sized between 1–10 nm adhere to bacterial cell membranes, disrupting membrane integrity and interfering with cellular respiration.
2. Once internalized, AgNPs interact with sulfur- and phosphorus-containing biomolecules, including DNA, disrupting replication and cellular function.
3. Additionally, AgNPs release silver ions (Ag^{+}), which contribute further to their bactericidal activity.

One common method for incorporating AgNPs onto titanium implant surfaces is the Tollens reaction, where silver is deposited in concentrations around 0.05 ppm. In a study conducted by Zhao et al., AgNPs were integrated into titania nanotubes (TiO_2-NTs) on the surface of titanium implants through a process involving silver nitrate immersion followed by ultraviolet irradiation. The results demonstrated effective inhibition of planktonic bacteria during the early days post-implantation and sustained prevention of bacterial adhesion for up to 30 days [29, 30].

Furthermore, Jia et al. investigated the biological response to varying concentrations of AgNP coatings. Their findings suggested that lower concentrations of AgNPs are more conducive to osteoblastic activity and bone integration, highlighting the importance of dosage in balancing antimicrobial efficacy and biocompatibility [31].

10. Biomimetic Surface Treatments

Biomimetic surface modification is an emerging area of research in implant dentistry, focused on replicating the biological environment to enhance osseointegration. Ideal biomimetic agents should fulfill several key criteria: they must promote cellular differentiation for bone formation, maintain strong adhesion without delamination, be easy and cost-effective to produce, chemically stable, and non-immunogenic [32].

Bone morphogenetic proteins (BMPs), particularly recombinant human BMP-2 (rhBMP-2), have been widely studied for their osteoinductive potential in dental applications. rhBMP-2 has demonstrated a strong ability to initiate and support bone formation around dental implants, with the newly formed bone contributing to long-term implant stability. Although the high cost of rhBMP-2 is a limiting factor, it offers the advantage of adhering effectively to various implant materials under physiological conditions [33].

Other promising biomimetic agents include RGD peptides (arginine-glycine-aspartic acid sequences), which have been shown to enhance the attachment of osteoblasts to treated titanium surfaces. Roessler et al. reported that RGD peptides not only improve cell adhesion but also enhance the performance of other biomaterial coatings [34].

Additionally, cytokines, platelet-rich plasma (PRP), and type I collagen have all demonstrated the ability to stimulate osteoblastic activity when applied to implant surfaces. Bisphosphonates, when immobilized on titanium implants, have been associated with increased bone density in the peri-implant region. However, achieving a controlled and sustained release of these drugs remains a technical challenge [35].

Furthermore, tetracycline-coated implants have shown dual benefits. According to Liao et al., tetracycline not only exhibits antibacterial activity but also removes the smear layer and inhibits collagenase, ultimately promoting bone regeneration around the implant site [36].

11. Conclusions

Numerous surface treatment techniques have been developed to enhance bone regeneration and reduce the duration of edentulousness for patients. When surface modifications are designed based on well-understood biological mechanisms, the beneficial properties of titanium can be more effectively harnessed. However, significant challenges remain—particularly in accurately characterizing implant surfaces, as many modification techniques are applied under conditions that do not replicate the natural physiological environment. Moreover, there is a limited number of clinical studies that demonstrate clear differences in implant survival rates based on varying surface characteristics. Future research should focus on creating surfaces with standardized topographies to enable more consistent evaluation of tissue responses. To advance our understanding of osseointegration, further investigations are needed into the processes of bone mineralization and the mechanical strength at the bone–implant (or coating–implant) interface on modified implant surfaces.

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