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An Overview Of Titanium Dental Implants

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Abstract:

- This review explores various aspects of using titanium and its alloys in dental implant manufacturing, highlighting common causes of implant failure and recent advancements in surface modification aimed at enhancing osseointegration and ensuring long-term implant success. Titanium and its alloys has increasingly popular engineering materials due to their exceptional strength-to-weight ratio and outstanding resistance to corrosion.
- The primary materials used for implants are commercially pure titanium (cp Ti) and the Ti-6Al-4V alloy, both of which demonstrate clinical success rates approaching 99% after ten years. These alloys are highly biocompatible with bone and gingival tissues and have the ability to integrate directly with bone through osseointegration. Despite continuous improvements in metallurgical techniques, materials science, and implant design, corrosion and mechanical failures still occur. Therefore, preventive approaches are crucial to minimize implant-associated infections. One effective strategy involves creating antibacterial implant surfaces that can inhibit biofilm formation and reduce microbial colonization.

Key words:

- Passivation, staphylococcus aureus, antimicrobial coatings, ionized-jet deposition, micro-arc oxidation, sol-gel processing, hierarchical scales, osteogenic cell, sandblasting, osseointegration, acid etching.

Introduction:

- Contrasted to steel and cobalt–chromium alloys, titanium is a relatively recent addition to surgical materials. Titanium alloys were initially developed for use in surgical implants in the 1960s, and their application in medical procedures has continued to expand steadily since the mid-1970s. In commerce pure titanium (cp Ti) implants are synthetic materials frequently employed in dentistry as the structural base for tooth replacement. One major concern with metallic implants is corrosion — the slow deterioration of materials caused by electrochemical reactions within the body. In the course of this process, elements from casting alloys may leach into the body over both short (days) and extended (months) periods.

What are titanium dental implants?

- Titanium dental implants are a widely preferred option for restoring missing teeth due to their strength, durability, and biocompatibility. Titanium dental implants are artificial tooth roots made from titanium metal, surgically placed into the jawbone toreplace missing teeth. They act as a base for attaching artificial teeth like crowns, bridges, or dentures.

Advantages:

1.Longevity: Titanium implants are known to last 20 years or more, making them a long-term solution for missing teeth.

2.Aesthetic Results: When paired with high-quality crowns, titanium implants offer a natural- looking result.

3.Functional Restoration: Implants restore both the form and function of missing teeth, improving chewing efficiency and speech. 4.Biocompatibility: The material is well-tolerated by the body, minimizing the risk of rejection or adverse reaction.

Considerations and limitations:

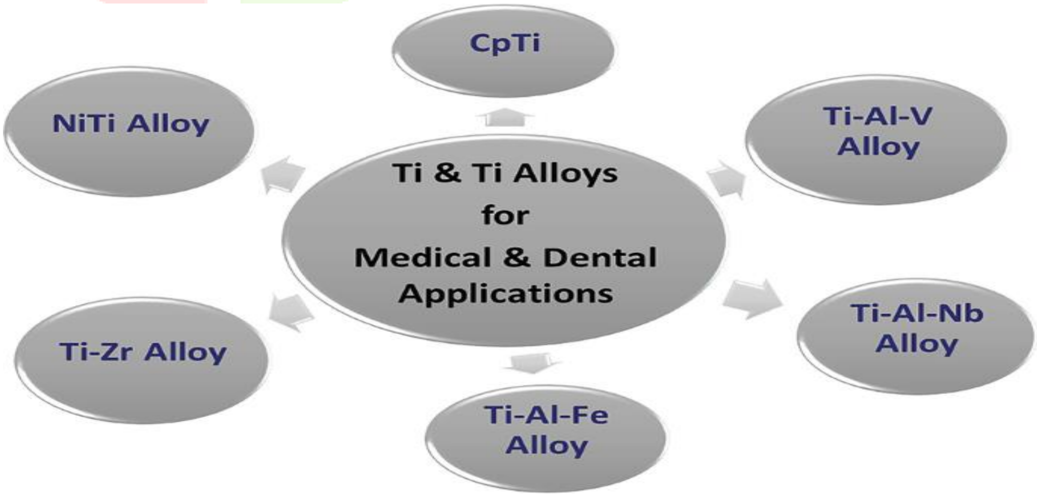
1.Titanium Particle Release: Studies have identified the presence of titanium particles inn peri-implant tissues, especially in cases of peri-implants. These particles can be released due to mechanical wear or corrosion, potentially leading to inflammation or tissue response.

2.Allergies Reactions: These are rare, some individuals may experience hypersensitivity, to titanium, leading to discomfort or implant failure.

3.Radiation Interferences: Titanium implants can scatter radiation during certain medical imaging procedures, such as proton therapy, potentially affecting treatment accuracy.

Titanium and its alloys as dental implants:

- In general, an alloy can be described as a combination of a metal with one or more additional elements that together exhibit metallic bonding characteristics. For titanium, multiple initiatives have been pursued to enhance its properties by incorporating elements such as silver (Ag), aluminum (Al), copper (Cu), iron (Fe), vanadium (V), and zinc (Zn).



Ti–Zr:

Zirconium (Zr) behaves as a neutral solute element when incorporated into titanium (Ti). As both elements belong to Group 4 of the periodic table, along with hafnium (Hf), they exhibit comparable crystal structures and similar physicochemical characteristics. Kobayashi *et al.*[9] investigated the mechanical and structural behavior of Ti–Zr binary alloys, including hardness, tensile strength, and microstructural features observed through optical microscopy. Their results demonstrated that Ti–Zr alloys containing up to 50 wt% Zr possessed higher hardness and tensile strength when contrasted with commercially pure titanium (cp–Ti) and pure zirconium. Similarly, Ho *et al.*[10] developed an experimental Ti–10Zr alloy that exhibited superior hardness and grindability relative to unalloyed Ti. Nevertheless, they noted that the alloy displayed inadequate strength and limited elastic recovery, rendering it unsuitable for certain dental applications requiring spring-back performance.

Ti–In:

For Ti–In binary systems, Wang[11] reported that the passivation current densities of Ti–In alloys and cp–Ti in artificial saliva were of comparable magnitude. Furthermore, Ti–10In and Ti–15In alloys (containing 10%wt and 15%wt indium, respectively) exhibited trans-passive behavior and lower current densities at elevated potentials in fluoride-containing media (Na F). Han *et al.*[12] further demonstrated that Ti–In alloys with indium contents ranging from 5 to 20% weightnot only maintained corrosion resistance when compared with cp–Ti but also exhibited superior oxidation resistance. These findings suggest that Ti–In alloys could provide corrosion performance identical to or exceeding that of cp–Ti, rendering them suitable candidates for biomedical applications.

Ti–Ag:

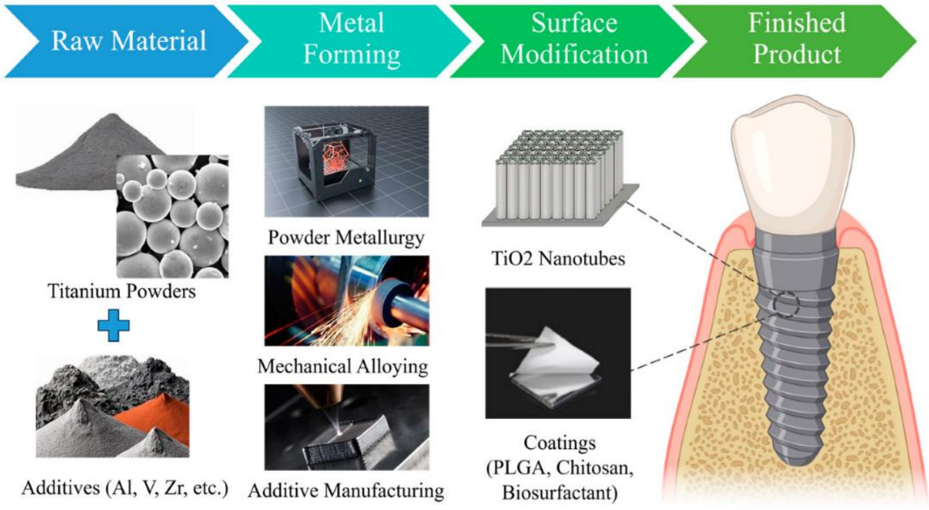
Oh *et al.*[13] reported that Ti–Ag alloys shows superior mechanical strength and elevated corrosion resistance compared with pure titanium, while maintaining similar biocompatibility profiles. This was corroborated by Zhang *et al.*[14] through *in vitro* cytotoxicity evaluations, which confirmed that Ti–Ag alloys and cp–Ti possess comparable cytocompatibility. Based on these observations, Ti–5Ag and Ti–20Ag compositions were recommended for dental applications, as they exhibit favorable passive film stability and minimal cytotoxic effects.

Ti–Cu:

Copper (Cu) has traditionally been employed in dental casting alloys owing to its favorable mechanical characteristics and ease of processing. Previous investigations[15] revealed that the binary Ti–Cu alloy exhibits a eutectoid structure near 7.0 mass% Cu, where an intermediate Ti_2Cu phase forms in the titanium-rich region. Alloys close to this eutectoid composition demonstrate increased strength accompanied by lower ductility compared to economically pure titanium (cp–Ti). Given these properties, Ti–Cu alloys are considered suitable for dental prosthetic components such as clasps, partial dentures, and bridges, where both strength and workability are critical.

Ti–Sn:

Tin (Sn) has been documented to be both biocompatible and nonallergenic when alloyed with titanium[16]. As an alloying element, Sn has been shown to augment the mechanical capabilities of Ti-based materials through solid-solution strengthening mechanisms[17]. Studies on binary Ti–Sn alloys have demonstrated favorable strength and ductility characteristics, suggesting their potential use in dental casting and other biomedical applications[18].



The effect of corrosion on titanium dental implants

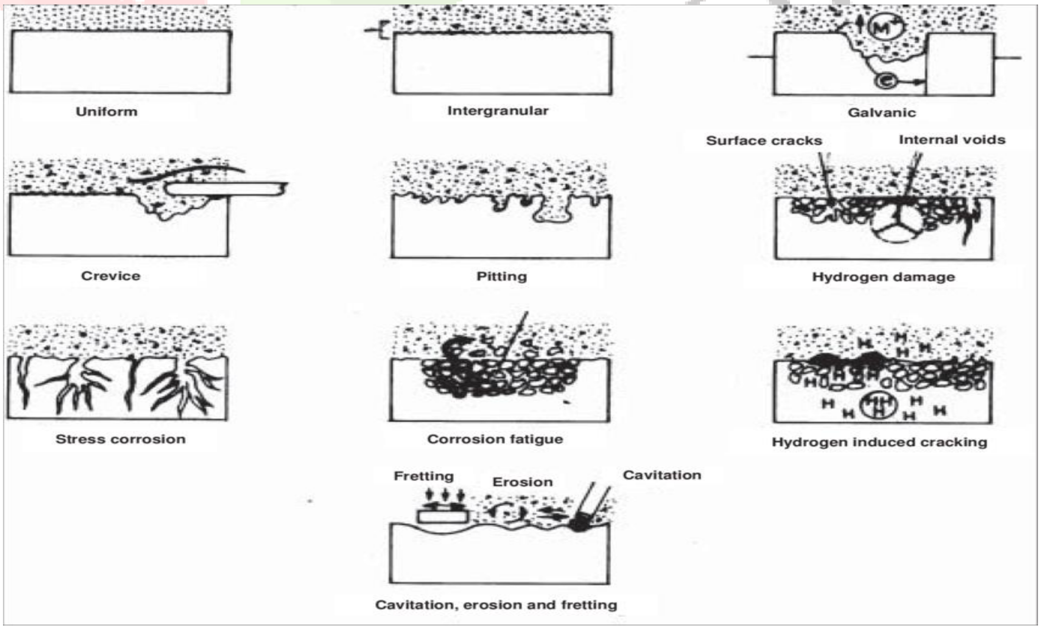
Corrosion behavior in the oral activity:

Multiple forms of electrochemical corrosion may arise within the oral cavity owing to the presence of saliva, which functions as a weak electrolyte containing various salts. The electrochemical characteristics of saliva are influenced by factors such as ionic concentration, pH, surface tension, and buffering capacity—all of which determine its ability to facilitate electrochemical reactions. Consequently, the extent and rate of corrosion processes in dental materials are governed by these variables.

Corrosion behavior in dental alloys is primarily influenced by two key aspects[19]:

1. The oxidation and reduction reactions occurring at the metal–electrolyte interface.
2. The presence of physical or chemical mechanisms that limit corrosion, such as **passivation**, where a stable metal oxide film is generated on the surface and inhibits further degradation.

Titanium and its alloys exhibit superior corrosion resistance in both saline and acidic environments due to the spontaneous formation of a protective titanium dioxide (TiO_2) passive film. Although this oxide layer provides excellent stability, titanium is not entirely immune to corrosion. When the passive layer is disrupted or fails to regenerate on localized regions of the surface, the exposed metal becomes susceptible to corrosive attack, behaving similarly to other base metals under such conditions.

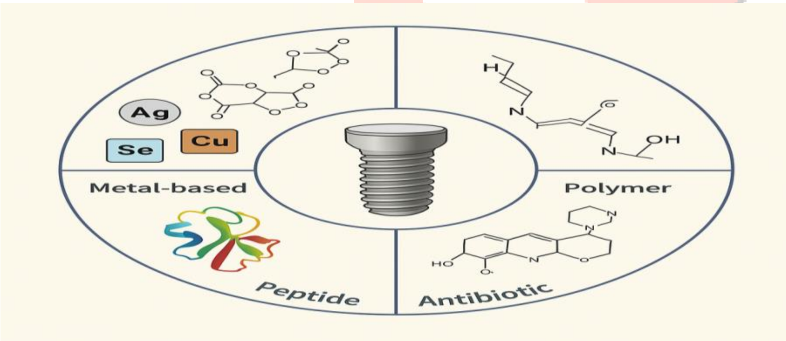


Types of corrosion

Anti-bacterial coatings for Titanium dental implants:

- Postoperative infection of tissues surrounding implant materials represents a major complication in orthopedic surgery.[20] Such infections not only compromise the success of the surgical procedure and the integrity of the implant but also significantly delay patient recovery.[21] Although systemic antibiotics remain the primary treatment option, their use is frequently linked to undesirable adverse side effects and the risk of developing antibiotic resistance.[22] Once bacteria colonize an implant surface, they can generate a biofilm—a structured microbial community encapsulated in a protective extracellular matrix—which markedly reduces the potency of antimicrobial agents.[23]

- The physicochemical characteristics of an implant's surface is fundamental in determining its engagement with host tissues and susceptibility to microbial adhesion. One among of the widely investigated approaches to prevent implant-associated infections (IAIs**)** involves coating titanium-based implants with antimicrobial agents. Among the various pathogenic microorganisms implicated in IAIs, the Gram-positive *Staphylococcus aureus* is the most extensively studied due to its strong biofilm-forming ability and capacity to evade host immune responses. These biofilms act as barriers, shielding bacterial cells from immune attack and conferring enhanced resistance to antibiotics. Other clinically relevant pathogens include the Gram-negative species *Pseudomonas aeruginosa*, *Porphyromonas gingivalis*, and *Escherichia coli*, as well as the Gram-positive *Staphylococcus epidermidis* and *Streptococcus sanguinis*.
- To be effective, antimicrobial coatings must not only inhibit bacterial colonization but also exhibit biocompatibility**,** non-cytotoxicity, and promote osseointegration. Coatings are typically produced by forming an additional functional layer on the implant surface without altering the mechanical or chemical attributes of the bulk material. Multiple fabrication methods exist, including electrochemical deposition**,** ionized jet deposition (IJD)**,** sol–gel processing, and micro-arc oxidation. For infection prevention, these coatings are often enriched with antimicrobial agents such as inorganic elements, antibiotics, antimicrobial peptides, polymers, or hybrid inorganic–



organic compounds. These modifications have the potential to effectively suppress biofilm formation.

Anti-bacterial coatings on titanium dental implants

Coatings with inorganic Anti-bacterial agents:

- To improve antibacterial performance and promote a favorable environment for tissue healing, inorganic bio-functional agents—including metallic ions, nanoparticles, and certain non-metal elements such as iodine and fluorine—are commonly incorporated into titanium surfaces. This incorporation can be accomplished either through direct deposition or by surface modification strategies such as electrochemical treatment, plasma ion implantation, plasma electrolytic oxidation, sol-gel processing, or micro-arc oxidation. The antimicrobial efficacy of these incorporated agents largely depends on their concentration and the rate at which the ions are released into the surrounding biological environment. Importantly, most inorganic antibacterial agents exhibit broad-spectrum activity rather than Gram-specific selectivity, thereby reducing the likelihood of developing antimicrobial resistance compared with antibiotic-based coatings[24].

Metal-Doped Coatings

- A variety of metallic elements—particularly transition metals—havebeen doped or co-doped onto titanium surfaces to improve the bioactivity and antibacterial properties of titanium-based implants. When used at optimal concentrations, certain metal ions and the oxide nanoparticles derived from can exert therapeutic effects. Typically, these ions are embedded within suitable substrates such as titanium dioxide (TiO_2) or bioactive glass[25], which are subsequently applied to the implant surface to enhance biological performance.

I. Silver (Ag)

- Among the various metallic dopants, silver (Ag) remains one of the most frequently utilized for titanium implant coatings due to its strong broad-spectrum antimicrobial activity, biocompatibility, and long-term chemical stability. Various investigations have established that silver nanoparticles not only hinder bacterial adhesion and growth but also modulate the manifestation of biofilm-forming genes in *Staphylococcus epidermidis* and *Staphylococcus aureus*[26].

II. Copper (Cu), Zinc (Zn), and Selenium (Se)

- Following silver, copper (Cu) and zinc (Zn) are among the most frequently employed dopants because of their intrinsic antibacterial properties, cost-effectiveness, and capacity to promote osteogenesis. Both copper and selenium (Se) are indispensable trace elements for normal physiological function, and coatings containing these ions have been demonstrated to enhance implant biocompatibility. Furthermore, zinc-containing coatings contribute to osteoblast differentiation and boost the corrosion resistance of titanium implants[27]. Notably, microporous Cu–TiO_2-coated titanium implants fabricated via micro-oxidation have demonstrated improved osseointegration at the bone–implant interface in animal models such as rabbit femoral condyles.

III. Other Metallic Dopants

- In addition to these elements, coatings incorporating calcium (Ca), strontium (Sr), gallium (Ga), bismuth (Bi), and various rare earth metals—including samarium (Sm), cerium (Ce), ytterbium (Yb), and erbium (Er)—have been explored to further enhance the bioactivity, osteo-conductivity, and overall biological performance of titanium substrates.

Coatings loaded with Antibiotics:

I. Antibiotic-Functionalized Coatings

- Numerous studies have explored the functionalization of titanium surfaces with antibiotic coatings to inhibit bacterial adhesion, biofilm formation, and biofouling, thereby reducing the likelihood of postoperative infections. The effectiveness of such coatings largely depends on achieving the appropriate antibiotic concentration and ensuring controlled, sustained drug release. However, the increasing prevalence of antibiotic-resistant bacterial strains have sparked serious apprehension regarding the long-term use of antibiotic-releasing coatings[28]. Clinical evidenceindicates that patients with peri-implantitis frequently harbor at least one antibiotic-resistant microorganism.

  Among various antibiotics, gentamicin is one of the most extensively employed agents for treating implant-associated infections. As an aminoglycoside, gentamicin displays significant bactericidal effects against a wide spectrum of aerobic Gram-negative bacteria, and its effectiveness is closely tied to drug concentration. Gentamicin-based coatings have been shown to promote osseointegration and prevent osteomyelitis, with demonstrated efficacy against *Staphylococcus aureus, Pseudomonas aeruginosa*, and *Escherichia coli*. Several other antibiotics that have been incorporated into titanium surfaces to prevent implant-associated infections (IAIs) include amoxicillin, vancomycin, tetracycline, rifampicin, and levofloxacin[29].

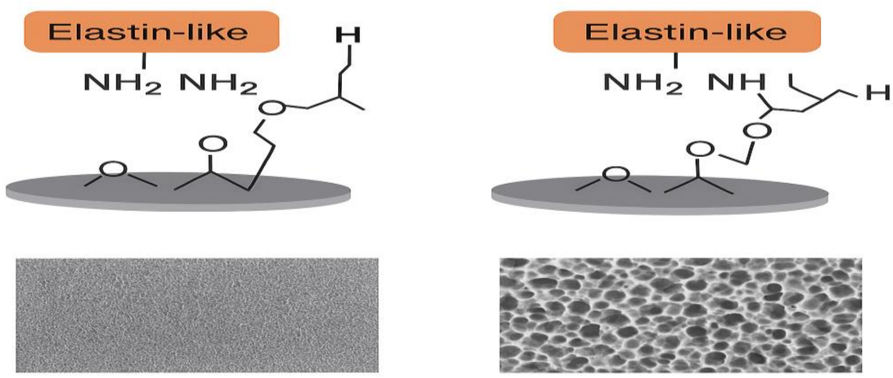
II. Polymer-Based Coatings

- Extensive use is made of both natural and synthetic polymers to develop antibacterial surface modifications for titanium implants, as they offer excellent flexibility and can be readily functionalized with bioactive molecules. Certain polymers—such as chitosan, polyethylene imines containing nitrogen, and quaternary ammonium compounds—exhibit intrinsic bactericidal activity, while others act as carriers for antibiotics or inorganic antimicrobial agents.
- Although antibiotic-loaded polymers provide effective antibacterial action, they frequently encounter limitations, including inadequate control of drug release and non-specific accumulation of antibiotics in tissues away from the implant site. In contrast, many natural polymers lack adequate mechanical strength and degrade rapidly, leading to non-uniform drug elution[30]. Toaddress these limitations, polymers are frequently combined with inorganic components such as metal oxides or hydroxyapatite (HAP) to improve their antibacterial efficiency and structural stability.
- Instead of using antibiotics as the active component, polymers can be chemically functionalized to impart inherent bactericidal properties. For instance, incorporating quaternary amine groups onto polymer chains transforms them into antimicrobial surfaces without the need for drug loading. A notable example includes chitosan microsphere/nano-HAP composite coatings on titanium surfaces, where ciprofloxacin was encapsulated within microspheres through diffusion and encapsulation techniques. The resulting coatings displayed antibacterial activity against*Staphylococcus aureus*, with the antibacterial efficacy influenced by both nano-HAP content and ciprofloxacin concentration[31]. Another study reported a poly-L-lysine (PLL)/sodium alginate (SA)/silver nanoparticle composite coating capable of preventing bacterial colonization while promoting mineralization and osseointegration *in vivo*.

III. Antimicrobial Peptide (AMP)-Based Coatings

- Antimicrobial peptide (AMP) coatings have recently emerged as a promising alternative to conventional antibiotic-based surface treatments for titanium implants. AMPs possess broad-spectrum antimicrobial activity, often requiring only low concentrations to achieve significant bacterial inhibition. Typically composed of 15–20amino acids, these short peptides contain both hydrophobic and hydrophilic residues, allowing them to interact with bacterial plasma membranes and cause cell lysis[32]. Depending on their structure, AMPs can be cationic or amphipathic, enabling electrostatic and hydrophobic interactions with microbial membranes.
- A particularly effective example involves the proline-arginine-rich and leucine-rich repeat protein (PRELP)-derived AMP, RRP9W4N, which was incorporated into mesoporous titanium-coated implants. This coating exhibited antibiofilm activity similar to that of the antibiotic cloxacillin while maintaining sustained peptide release. *In vivo* studies using rabbit tibia models demonstrated that osseointegration remained unaffected, and a twofold increase in bone-to-implant contact (BIC%)—the percentage of the implant surface directly integrated with bone—was observed in AMP-coated samples compared with uncoated controls.

Surface Treatments of Titanium Dental Implants:



- The **clinical success** of titanium dental implants is closely associated with their ability to achieve early osseointegration. The implant's geometry and surface topography play critical roles in both short- and long-term clinical outcomes. Upon implantation, titanium immediately interacts with biological fluids and surrounding tissues, initiating a cascade of physicochemical and biological events. **Direct bone apposition** onto the titanium surface is essential for rapid implant stabilization and early functional loading.

Chemical Composition of the Implant Surface:

- The chemical structure and surface charge of titanium implants vary depending on both the bulk alloy composition and the applied surface treatments. These parameters critically influence protein adsorption, cell adhesion, and subsequent bone formation. Most dental implants are fabricated from commercially pure titanium (cp-Ti) or titanium alloys. Cp-Ti is classified into four grades (Grades 1–4) based on its impurity content—primarily oxygen, carbon, and iron—which affect its mechanical strength and corrosion resistance. Alloying elements are often introduced to improve mechanical properties while maintaining biocompatibility.

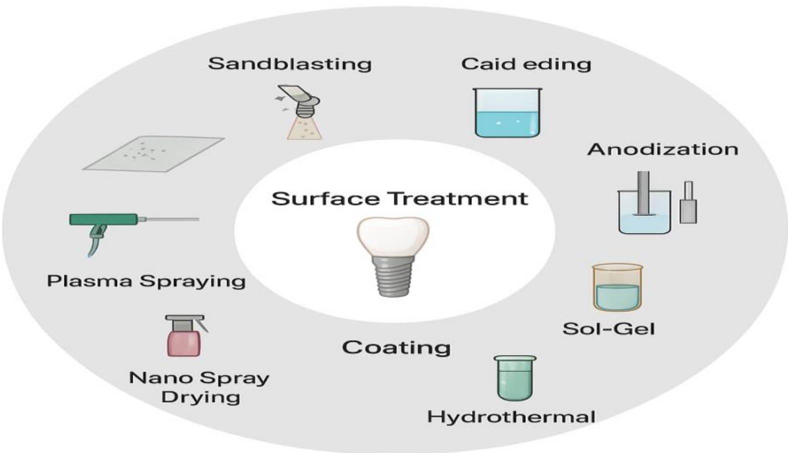
Surface Roughness of Titanium Implants:

- Extensive research has demonstrated that surface roughness significantly affects the rate of osseointegration and the biomechanical stability of titanium implants. Surface roughness can be described across three hierarchical scales: macro-, micro-, and nano-topography.

- The macro-scale (ranging from millimeters to tens of micrometers) primarily relates to the overall implant geometry, such as the threaded screw design or macro-porous structures, which enhance mechanical interlocking with bone tissue.
- The micro-scale features (1–10 µm) influence cell attachment, proliferation, and differentiation.
- The nano-scale modifications (below 1 µm) affect protein adsorption and cell–surface signaling, promoting rapid osteogenic activity at the bone–implant interface.

Osteoconductive Calcium Phosphate Coatings:

- Metallic implants are frequently coated with calcium phosphate (CaP) materials, particularly hydroxyapatite (HAP), to enhance osteo-conductivity. Upon implantation, the gradual dissolution of calcium and phosphate ions from the coating increases the local ion concentration in the peri-implant region, leading to biological apatite precipitation on the implant surface. This biologically formed apatite layer often incorporates endogenous proteins, serving as a scaffold for osteogenic cell attachment, proliferation, and extracellular matrix formation.
- The subsequent bone healing process involves osseointegration, a direct structural and functional connection at the interface of implant surface and the surrounding bone. This fusion provides a stable and durable interface, enabling long-term clinical success of dental implants[33].



surface treatments of titanium dental implants

- Surface modification techniques are widely applied to titanium dental implants to improve their osseointegration, biocompatibility, and long-term stability. Among the most studied methods are plasma spray coating, acid etching, dual acid etching, and sandblast–large grit–acid etching (SLA). Each approach aims to enhance surface roughness and chemical reactivity, thereby promoting cellular adhesion and bone tissue integration.

A. Plasma Spray Coating

- The plasma spraying technique involves the deposition of a thick coating layer—commonly composed of hydroxyapatite (HA) or titanium (Ti)—onto the implant substrate. In this process, the coating material is thermally melted and projected onto the implant surface under high energy, resulting in a uniform, adherent layer. HA-coated titanium alloys have received substantial attention due to their excellent biocompatibility, osteo-conductivity, and mechanical stability. The plasma-sprayed coating substantially increases the implant's surface area and roughness, thereby enhancing osseointegration[34].
- Another widely employed surface roughening technique is grit blasting, which involves the projection of pressurized abrasive particles—such as alumina, titanium dioxide (TiO_2), hydroxyapatite, or silica—onto the implant surface[35]. [36] This method increases surface roughness and microhardness, providing a more favorable substrate for bone cell attachment. Typically, acid etching follows grit blasting to remove residual particles and contaminants. However, grit blasting can also embed trace particles incorporated into the substrate, potentially altering its surface chemistry. Notably, the utilization of zirconia particles in grit blasting has been shown to significantly increase the surface microhardness compared with polished titanium surfaces.

B. Acid Etching

- **Acid etching** is a chemical surface modification technique that employs strong acids to both clean and texture the titanium surface. Commonly used acids include hydrofluoric acid (HF), nitric acid (HNO_3), sulfuric acid (H_2SO_4), or their combinations. This treatment creates micro- and nano-scale roughness, improving cell adhesion, osteoblast differentiation, and bone formation around the implant. The resulting increase in surface reactivity and topographical complexity enhances osseointegration and early-stage implant stability.

C. Dual Acid Etching (DAE)

- Dual acid etching (DAE) involves treating the implant surface with two different acids, either sequentially or simultaneously, to achieve a controlled and uniform micro-rough surface. This method has been shown to promote rapid osseointegration by generating topographical features conducive to bone tissue growth. Comparative studies between machined implants and DAE-treated surfaces (e.g., using HF followed by HCl/H_2SO_4) have demonstrated that DAE surfaces exhibit higher reverse torque resistance and superior bone-to-implant contact, confirming improved interfacial bonding.

D. Sandblast–Large Grit–Acid Etching (SLA)

- The SLA technique combines grit blasting and acid etching in a sequential process to create multi-scale surface textures. Initially, large-grit sand particles are blasted onto the titanium surface to introduce macro-roughness, followed by strong acid treatment to generate micro-pits and enhance surface reactivity. This dual-level roughness optimizes both mechanical interlocking and biological response, leading to enhanced osseointegration and accelerated bone healing. SLA-treated implants have emerge as one of the most clinically validated surface modifications in contemporary implantology.

Conclusion:

Titanium dental implants have transformed prosthetic dentistry by offering durable, biocompatible, and highly reliable solutions for tooth replacement. Their clinical success is largely attributed to their superior ability to achieve osseointegration, excellent mechanical strength, and long-term stability within the oral environment. The performance of titanium implants can be further enhanced through various surface modification techniques such as anodization, sandblasting, acid etching, and the application of bioactive or antimicrobial coatings, all of which promote stronger bone–implant interactions.

Although alternative materials like zirconia are gaining attention for their aesthetic and biological advantages, titanium remains the gold standard due to its well-established track record and adaptability in diverse clinical scenarios. Looking ahead, future research should emphasize strategies that enhance the biofunctionality of implant surfaces, shorten healing periods, and improve both tissue integration and antibacterial performance, thereby advancing the next generation of dental implant technologies.

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