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TREATMENTS AND METHODS FOR IMPROVING BIOFUNCTIONAL PROPERTIES OF TITANIUM ALLOYS

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Abstract

Because of its exceptional combination of mechanical strength, corrosion resistance, and outstanding biocompatibility, titanium and its alloys continue to be essential in the development of cutting-edge biomedical implants. But choosing the right alloy system is not enough to provide maximum clinical performance; coordinated engineering of chemical composition, microstructure, and surface functioning is also necessary. This article offers a comprehensive summary of current developments in the design of non-toxic β-stabilized titanium alloys, thermomechanical processing to regulate microstructural characteristics, and nanoscale surface modification to improve biological responses. Stress shielding effects have been successfully mitigated by new alloy systems based on Nb, Ta, Zr, Mo, and Sn, which have shown notable gains in elastic modulus reduction, phase stability, and biomechanical compatibility. Strength, ductility, fatigue resistance, and changeable stiffness can be improved by precisely altering grain size, α/β phase distribution, and defect structures through microstructural optimization via solution treatment, aging, severe plastic deformation, and hot working. Anodization, acid and alkaline treatment, sol-gel deposition, and chemical vapor deposition are examples of complementary surface engineering techniques that create bioactive, nanostructured surfaces with antimicrobial or anti-inflammatory qualities, enhance corrosion resistance, and speed up osteointegration. A new paradigm in multifunctional titanium biomaterials that combine surface characteristics, microstructure, and composition optimization has emerged, one that may provide mechanical reliability with biological intelligence. This unified strategy will be useful in developing next-gen orthopedic and dental implants that integrate with the body more effectively, last longer, and provide superior clinical outcomes.

Keywords: *Titanium alloys; Biofunctional properties; Surface modification; Thermomechanical processing; β-stabilizing elements; Osteointegration; Nanostructured surfaces; Severe plastic deformation; Calcium phosphate coatings; Biomedical implants*

Introduction

The advancement of metallic biomaterials for orthopedic and dental applications has progressed markedly in recent decades, mostly because to the increasing demand for durable,

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safe, and biocompatible solutions for musculoskeletal disorders. Titanium and its alloys are essential among metallic materials utilized in clinical practice due to their exceptional properties, which render them suitable for implantation, including remarkable mechanical strength, low density, excellent corrosion resistance, and superior biocompatibility [1–3]. Nonetheless, titanium-based implants, particularly prevalent types such as Ti–6Al–4V, have some significant disadvantages. This encompasses mechanical incompatibilities between the implants and adjacent bone tissues, the potential for dangerous alloying element leakage, and insufficient promotion of osseointegration [4–7].

Recent research has focused on developing novel, non-toxic titanium alloys with diminished elastic moduli and enhanced biomechanical properties to mitigate these challenges. Nb, Ta, Zr, Mo, and Sn are alloying elements frequently employed in this context due to their ability to stabilize the β phase in titanium [8–9]. Simultaneously, various heat treatments and plastic deformation techniques are employed to enhance the precipitation of alloy phases, stabilize the α/β phase distributions, and refine microstructural characteristics, resulting in titanium alloys tailored for specific biomedical applications [10–11].

Recent surface modification approaches have revealed an alternative method to enhance the biofunctionality of titanium alloys, particularly concerning their interaction with biological tissues. The fabrication of bioactive nanostructured surfaces is facilitated by techniques such as anodization, chemical vapor deposition (CVD), sol-gel processing, and acid/alkaline etching. These surfaces significantly enhance osteogenesis, diminish bacterial adhesion, and improve corrosion resistance [12–13]. Coatings composed of calcium phosphates and functional nanoparticles have demonstrated a significant capacity to enhance in situ biological apatite formation, leading to rapid and effective osseointegration of implant surfaces [14–15].

The creation of next-generation biomedical implants ultimately depends on the synergistic optimization of titanium alloys' chemical composition, microstructure, and surface properties. In order to improve the clinical performance and functional characteristics of titanium-based implants in contemporary medical applications, this article will provide a thorough examination of recent developments in alloy design and heat treatment techniques applied to titanium, as well as new nanoscale surface modification techniques.

Development of Next-Generation Titanium Alloys

Non-toxic alloying elements

Current developments in biomedical materials have concentrated on creating titanium alloys with non-toxic β-stabilizing elements like Nb, Ta, Zr, Mo, and Sn. These components are essential in lowering the elastic modulus and improving biomechanical compatibility, which helps to solve a major issue with conventional titanium alloys like Ti–6Al–4V. Although titanium alloys are well known for their superior corrosion resistance and biocompatibility when compared to other metallic materials such as stainless steels and Co-Cr alloys, they still have major drawbacks at the bone–implant interface, mainly because of stress shielding effects that can jeopardize bone viability and implant longevity [16–17].

One of the most fundamental issues in designing load-bearing implants is the mechanical mismatch between the Young's modulus of bone, which normally varies from 10 to 40 GPa, and the substantially higher modulus of standard implant materials, such as Ti–6Al–4V, which averages around 110 GPa. Localized bone resorption and ultimately implant failure may arise from this disparity. For body-centered cubic (BCC) Ti–X–Y alloys, where X and Y stand for the alloying elements, computational modeling techniques have been used to predict the elastic stiffness coefficients at the single-crystal level. When the compositions of ternary alloys from systems such as Ti–X–Y (where X and Y are Mo, Nb, or Ta) and Ti–X–Sn approach the BCC stability limit, which is linked to a reduced elastic modulus, research suggests that these alloys have promising mechanical properties [18,19].

The biological interaction of metallic implants with the physiological environment is essential even more so than their mechanical compatibility. Concerns about the possible cytotoxicity of aluminum and vanadium are raised by historical reliance on conventional titanium alloys, such as Ti–6Al–4V and commercially pure titanium (CP–Ti), since research has connected these elements to harmful neurological effects and metal buildup in surrounding tissues. Research on creating non-toxic, non-allergic titanium alloys with β-stabilizing components including Nb, Ta, Zr, Mo, Sn, Pt, and Pd has been sparked by this. These components help produce titanium alloys with low elastic modulus, high mechanical strength, and enhanced biocompatibility and electrochemical characteristics in addition to stabilizing the β phase at room temperature [20–21].

Even non-toxic metals can release metal ions or wear debris, which may adversely affect biological systems. This is another significant issue to consider. The stimulation of macrophages by wear particles from metallic joint implants can initiate an osteolytic response and promote osteoclast-mediated bone resorption. Investigations on alloys like Ti–1Fe, Ti–5Al–11Fe, and Ti–16Mo–3.2Nb exhibit behaviors akin to CP–Ti; conversely, Ti–6–7Nb demonstrates minor mitochondrial suppression attributed to Al ion leaching, while Ti–10Cu encounters complications due to excessive copper ion release. Conversely, Ti–Au alloys have exhibited remarkable 100% cell viability and exceptional cytocompatibility [22–24].

Moreover, the incorporation of manganese (up to 8 wt.%) has been shown to improve cytocompatibility. Alloying elements including Zr, Sn, Nb, Ta, and Pd, when utilized as binary constituents, not only stabilize the β phase but also markedly affect mechanical properties. For example, augmenting Sn and Zr concentrations linearly improves mechanical strength up to 15 wt.%, with Sn demonstrating more efficacy than Zr. Nonetheless, the strengthening contributions of Nb, Ta, and Pd (as β-eutectoid formers) are rather insignificant. Multi-element alloys, such as Ti–10%Sn–(4–8%)Nb–2%Ta–0.2%Pd, demonstrate enhanced strength relative to alternatives like Ti–10%Zr–(4–8%)Nb–2%Ta–0.2%Pd, highlighting the promise of meticulously designed compositions in the development of titanium alloys for biomedical applications [6,19,25,26].

The development of next-generation titanium alloys highlights a balanced strategy that integrates mechanical and biological compatibility via deliberate alloying and processing techniques. The emphasis on non-toxic β-stabilizer components, along with sophisticated modeling and characterization methods, is expected to improve the performance and safety of titanium-based implants across various biological applications (table 1).

Table 1. Classification of Biomedical Titanium Alloys: Composition, Phase Structure, Mechanical & Biological Performance

Alloy Category	Representative Compositions	Phase Type	Young's Modulus (GPa)	Mechanical Characteristics	Biological Behavior	Advantages	Limitations
Commercially Pure Titanium (CP-Ti, Grades 1–4)	Ti ≥ 99.5% (O, Fe, C, N as minor impurities)	α (HCP)	**100–110**	Moderate strength, low hardness, good fatigue resistance	Excellent cytocompatibility; stable TiO_2 passive film	Gold standard for biocompatibility; high corrosion resistance	High modulus → stress shielding; not ideal for load-bearing implants
α Alloys (non-heat treatable)	Ti–5Al–2.5Sn, Ti–3Al–2.5V, Ti–0.3Mo–0.8Ni	α	**95–110**	Good creep resistance; good weldability; limited strengthening	Good biocompatibility, stable oxide	Good for non–load-bearing implants & dental parts	High modulus; limited strength improvement; Al and V cytotoxicity issues

Alloy Category	Representative Compositions	Phase Type	Young's Modulus (GPa)	Mechanical Characteristics	Biological Behavior	Advantages	Limitations
Near-α Alloys	Ti–6Al–2Sn–4Zr–2Mo–Si	α-dominant with small β	**95–105**	High-temperature strength; used in aerospace more than biomedical	Acceptable biocompatibility	Improved creep & fatigue performance	Contain toxic Al/V; rarely used in implants
α+β Alloys (conventional biomedical)	**Ti–6Al–4V**, Ti–6Al–7Nb, Ti–6Al–2Sn–4Zr–6Mo	α + β	**105–120**	Good balance of strength/ductility; heat treatable	Good biocompatibility for Ti–6Al–7Nb; Ti–6Al–4V associated with V/Al ion release	Widely available; strong clinical history; good fatigue	Cytotoxicity concerns (Al, V); high modulus causes stress shielding
Metastable β Alloys (non-toxic)	**Ti–Nb**, **Ti–Nb–Zr**, **Ti–Nb–Ta–Zr**, **Ti–Mo**, **Ti–Mo–Zr–Sn**, Ti–15Mo, Ti–24Nb–4Zr–8Sn	β (BCC)	**40–85**	High elasticity, excellent cold workability, low modulus; good fatigue	Outstanding cytocompatibility; reduced inflammatory response	Low modulus (close to bone); no toxic ions; tunable properties	Lower strength unless thermomechanically treated; β → ω transformation risk
Biocompatible β-Type Multicomponent Alloys (<10 elements)	Ti–29Nb–13Ta–4.6Zr (TNTZ), Ti–25Nb–10Zr–8Sn, Ti–18Mo–6Nb–5Ta	β	**50–70**	High strength-to-modulus ratio; highly stable β phase	Strong osteogenic response; ideal for orthopedics	Excellent elastic behavior; customizable properties	Complex alloying → higher cost; processing-sensitive
β Shape Memory & Superelastic Alloys (Ni-free)	**Ti–Nb–Sn**, **Ti–Mo–Sn**, Ti–24Nb–7Sn	β → α″ martensite	**25–60**	Superelasticity; 1–3% recoverable strain	Good osteoblast response; low cytotoxicity	Ideal for spinal, orthodontic, and dynamic implants	Requires precise composition control; temperature sensitivity
Porous Titanium & Porous β Alloys (PBF, SLM, PM)	Pure Ti, Ti–Nb, Ti–Ta–Mo; porosity 10–70%	α or β foams	**5–40**	Bone-like modulus; adequate compressive strength (50–1500 MPa depending on porosity)	Promotes bone ingrowth; mimics cancellous bone	Excellent osseointegration; reduced stress shielding	Risk of reduced fatigue & corrosion; need for pore size optimization
Ti-Based Composite / Coated Systems	Ti + HA, Ti + CaP, Ti + bioactive glass, Ti–graphene	Depends on substrate	**Variable**	Coating improves functional behavior	Strong enhancement of early osteogenesis	Bioactive/antibacterial surface; tailored biology	Coating delamination risk; needs standardized processing

Microstructural modification through thermal treatments

Heat treatments are essential for modifying the microstructure of titanium alloys, thereby affecting their mechanical and biological properties in biomedical applications. Methods include solution treatment, aging, annealing, and controlled cooling are utilized to modify the distribution, morphology, and stability of the α, β, and ω phases of titanium, enhancing functionality and performance in implant applications.

The primary goal of these thermal treatments is for achieving thermodynamic stability among the constituent phases, namely stabilizing the β phase at ambient temperature. The β phase is essential for decreasing the Young's modulus of titanium alloys to levels comparable to natural bone (about 10–40 GPa), hence alleviating the stress shielding effect often associated with conventional alloys such as Ti–6Al–4V (roughly 110 GPa). The modulus mismatch may result in bone resorption and subsequent implant failure; thus, reducing this mismatch will be essential for improving long-term implant life and usefulness [27, 28].

Recent studies have concentrated on forecasting the elastic characteristics of titanium alloys by single-crystal elastic stiffness coefficients (cij), specifically for body-centered cubic (BCC) Ti–X–Y systems, where X and Y encompass elements such as Mo, Nb, Sn, Ta, and Zr. Alloys with compositions around the BCC stability barrier have been shown to possess the lowest elastic modulus, highlighting the significance of thermal stabilization of the β phase [29,30]. By employing meticulously regulated heat treatments, one can maintain or augment the β phase fraction while controlling the likely emergence of α or ω phases, which may compromise the alloy's ductility.

Heat Treatments and Biological Performance

Numerous investigations have validated the influence of heat treatments on the biological compatibility of titanium alloys. Storti et al. investigated the impact of high-temperature treatments (1000 °C for 24 hours in an inert atmosphere) on several alloys, including Ti–35Nb, Ti–35Nb–7.5Ta, Ti–35Nb–4Sn, and Ti–25Nb–15Zr. The findings indicated increased biomolecule adhesion and decreased oxidative stress in osteoblast cells, illustrating enhanced cell-material interactions [31]. Scanning electron microscopy (SEM) demonstrated substantial alterations in the surface and microstructural characteristics following treatment, suggesting enhanced cellular affinity and integration.

In a comparable context, research on Ti–20Nb alloys demonstrated that hot die forging at 780–860 °C, succeeded by heat treatment at 1000 °C for 8 hours, efficiently stabilized the β phase. This treatment produced a distribution of α precipitates inside the β matrix, advantageous for both biomechanical and biocompatibility properties [32]. These enhancements are essential for guaranteeing that the implants preserve structural integrity while promoting advantageous biological responses.

Interaction Between Porosity, Heat Treatment, and Mechanical Behavior

Heat treatments play a key role in alloys engineered with controlled porosity. The porous Ti–16Nb alloys, fabricated using powder metallurgy and sintered at 1200 °C for 3 hours, exhibited porosity values ranging from 4% to 60%. The regulated porosity markedly affected mechanical parameters, with heightened porosity associated with decreases in density (4.67 to 1.86 g/cm^3), elastic modulus (96 to 15 GPa), compressive strength (1450 to 100 MPa), and fracture strength (1173 to 97 MPa) [32]. Enhanced porosity improves biomechanical compatibility with bone but also introduces problems associated with increased corrosion, underscoring the necessity for thermally tailored microstructures to concurrently achieve mechanical performance and corrosion resistance.

Heat Treatments in Multicomponent Systems

The reaction of titanium alloys to thermal treatments is significantly influenced by composition, especially in multicomponent systems like Ti–Nb–Mo–Ta. Hot isostatic pressing, succeeded by thermal treatment, shown a decrease in compressive strength (from 1470 to 883 MPa) and grain refinement with elevated molybdenum equivalence [33]. Moreover, an increased molybdenum concentration modified the α-phase morphology, reducing the presence of network-like α, lamellar α, and Widmanstätten structures when the molybdenum amount surpassed 15 wt.%. Alloys like Ti–25Nb–5Mo–3.5Ta and Ti–25Nb–8Mo–3.5Ta attained excellent yield strength (900–1000 MPa), elastic modulus, and phase stability via meticulous thermal management.

The microstructural response to heat regulation in the Ti–Nb–Sn system is notably advantageous. The incorporation of Nb stabilizes the β phase and diminishes the elastic modulus, whilst Sn improves elastic recovery and affects the chemistry of the oxide coating. Alloys such as Ti–10Nb–xSn demonstrate transitions from dendritic β regions to lamellar α + β structures as Sn content increases, resulting in microstructural refinement and reduced porosity [34]. These modifications directly influence mechanical strength, corrosion resistance, and wear characteristics.

In summary, the implementation of heat treatments, with meticulous alloy composition adjustments, is essential for the development of titanium biomaterials that demonstrate optimized mechanical compatibility, superior corrosion resistance, and increased cellular connections. These innovations facilitate the development of the next generation of titanium-based implants, appropriate for diverse biomedical purposes.

Plastic deformation techniques

Plastic deformation methods are crucial for modifying the microstructure, mechanical properties, and functional characteristics of titanium-based biomaterials. Processes such as hot rolling, forging, extrusion, and severe plastic deformation (SPD)—including equal channel angular pressing (ECAP), high-pressure torsion (HPT), and multi-axial forging—facilitate substantial grain refinement, phase redistribution, and defect engineering. These alterations enhance strength, ductility, fatigue resistance, and biofunctional characteristics, rendering them especially attractive for biomedical implants [35, 36].

Among these technologies, SPD techniques are distinguished for their efficacy in generating ultrafine-grained (UFG) and nanocrystalline microstructures, which exhibit substantial enhancements in mechanical compatibility with biological tissues. The mechanisms of plastic deformation promote the refinement of β grains and the redistribution of α precipitates, so reducing the elastic modulus while preserving sufficient strength. This enhances the compatibility of titanium alloys with the mechanical characteristics of human bone [37].

The Ti–10Nb–xSn system illustrates how alloying and deformation can alter mechanical properties. As the Sn level in the alloy rises, the elastic modulus gradually diminishes (from around 73 to 76 GPa), nearing values comparable to those of cortical bone. Interestingly, whereas initial increments of Sn lead to diminished Vickers hardness and compressive strength, these characteristics start to improve as Sn concentration attains 5 wt.%, resulting in hardness values of 310–390 HV and compressive strength between 1100 and 1370 MPa [38].

The impact of Sn also affects tribological behavior, as the coefficient of friction rises from 0.41 to 0.50 with increasing Sn content. This study reveals that Ti–10Nb predominantly experiences abrasive wear in the absence of Sn, but the incorporation of Ti–10Nb–3Sn and Ti–10Nb–5Sn results in a hybrid adhesive–abrasive wear mechanism, ultimately shifting to largely adhesive wear in alloys containing 8 wt.% Sn. The Ti–10Nb–xSn alloys, fabricated using powder metallurgy and plastic deformation methods, are positioned as viable alternatives for biomedical applications requiring significant load-bearing capacity and endurance [39,40].

Nickel-free titanium shape memory alloys (SMAs), specifically those consisting of Ti–Mo–Sn, demonstrate enhanced advantages from plastic deformation processes. The inclusion of Sn in Ti–8Mo improves the stability of the β phase at ambient temperature, particularly for Sn concentrations ranging from 13 to 15 wt.%. The distortion of the β lattice in the β direction [41] not only promotes the β to α" martensitic transformation—essential for superelastic behavior—but also diminishes at a rate of –0.26% per wt.% Sn, hence enhancing favorable mechanical responses during operation [42].

Table 2. Summary of SPD Techniques and Their Effects

SPD Technique	Key Microstructural Effects	Main Outcomes
ECAP (Equal Channel Angular Pressing)	Ultrafine grains; α/β redistribution	Higher strength; improved fatigue; better osteoblast adhesion
HPT (High Pressure Torsion)	Nanocrystalline structure; strong grain refinement	Very high hardness; high wear resistance; enhanced bioactivity
MAF (Multi-Axial Forging)	Fine grains; uniform deformation	Higher strength + ductility; good osseointegration compatibility
ARB (Accumulative Roll Bonding)	Layered ultrafine grains	Increased tensile strength; improved bioactivity
Cryo-SPD	High defect density; nanotwins	Higher strength; improved wear & corrosion resistance
Hot Rolling / Forging	Refined β grains; controlled α precipitation	Balanced strength/ductility; stable surface for coatings
Friction Stir Processing (FSP)	Refined stirred zone; homogenized phases	Improved wear and fatigue; better cell response

The combination of plastic deformation and controlled Sn additions results in remarkable properties for these alloys, including:

- Recovery strains of up to 3.1%,
- Elastic strains ranging from 1.0% to 1.56%,
- Stable superelastic behavior at room temperature.

These unique properties are particularly valuable for applications requiring elasticity, damping, and adaptability, such as in orthodontic devices and spinal fixation systems [37, 42].

Surface Modification Strategies

Surface modification techniques are essential for enhancing the biofunctional efficacy of titanium and related alloys, especially in dental and orthopedic implants. The mechanical response of an implant is determined by its bulk composition and microstructure, although it is the surface that initially engages with the biological environment. The nanoscale modification of surface topography and chemistry can convert bio-inert metallic substrates into bioactive, osteoconductive, and osteoinductive surfaces, facilitating swift and stable osteointegration while reducing negative tissue responses (Table 3).

Nanoscale surface texturing

Over the past decade, dental implants have shown major advancements, with osteointegration continuing to pose a primary problem due to the considerable disparity in mechanical and chemical properties between metallic materials and human tissues. Upon the introduction of an implant or synthetic material into the body, the adjacent tissue reacts swiftly, influenced by surface chemistry, roughness, and topography. Bio-inert metals, like titanium and stainless steel, typically demonstrate restricted and occasionally adverse interactions with host tissue. Nanoscale surface texturing has emerged as an effective method to improve the implant-tissue interface, addressing these constraints [43, 44].

Nanostructured surfaces may control biological responses by affecting protein adsorption, focal adhesion development, and cytoskeletal arrangement. Hybrid nanocomposite coatings for dental implants, such as Ti–gelatin–gold systems, have demonstrated improved biocompatibility by enhancing connections among cell-survival pathways, neural signaling pathways, and cell-adhesion molecules in vitro [45]. Likewise, nanostructured synthetic dental materials including zinc and titanium dioxide can offer concurrent antibacterial and osteogenic properties, enhancing the biological seal and diminishing infection risk.

Table 3. Surface Modification Techniques, Morphology, and Functions

Technique	Resulting Morphology	Main Functions / Properties
Anodization	Ordered **TiO_2 nanotubes** (≈50–100 nm diameter) formed on Ti substrate	↑ Surface area; ↑ Osteoblast adhesion; ↑ Bone–implant contact; Enhanced bioactivity
Acid / alkaline etching	**Micro- and nano-roughened** surface with pits, nanoroughness, increased surface activation	↑ Osteoconductivity; Improved wettability; Faster biological apatite formation; Increased protein adsorption
Sandblasting + Acid Etching (SLA)	**Macro-rough** surface with **micro-pits**, hierarchical topography	↑ Torque removal; Strong mechanical interlock; Enhanced early osseointegration
Sol–gel CaP / HA coating	**Thin, uniform CaP/HA layer**; porous, nanostructured film	Bioactive coating; Controlled degradation; Ion release → stimulated osteogenesis; Supports bone mineral nucleation
CVD coatings (graphene, diamond, nano-ceramic)	**Ultra-thin conformal layer** (graphene/diamond/ceramic)	↑ Hardness; ↑ Wear resistance; ↑ Cell adhesion and mineralization; Chemical stability
Micro-arc oxidation (MAO)	**Thick porous oxide** with micro-pores; Ca/P incorporation; ceramic-like surface	↑ Corrosion resistance; ↑ Bioactivity; Supports osseointegration; Improved wettability

Nanomaterials situated at important interfacial regions of the implant can influence the development of fibrous capsules, which frequently occur as a reaction to foreign substances. By meticulously regulating nanoscale roughness and chemical composition, one can diminish fibrous encapsulation and promote direct bone contact. Furthermore, nanoparticles can discharge functional ions more swiftly than microscale particles, facilitating a more quick biological reaction. Their diminutive size enhances absorption by adjacent bone tissue, rendering them ideal carriers for the targeted administration of therapeutic medicines [46].

An illustration is the application of nanocarbonate bioactive coatings on dental implants situated near bone. These coatings initiate ionic exchanges between the implant surface and bodily fluids, resulting in the development of a bioactive surface layer. Bioactive compounds, including tricalcium phosphate and poly(lactic-co-glycolic acid) (PLGA) copolymers, might enhance osteointegration by serving as vehicles for osteogenic signals [47, 48]. Nanoscale texturing is a crucial enabling technology for the design of surfaces that facilitate rapid bone regeneration, enhance osteoblast activity, and ensure long-term implant durability.

Electrochemical and chemical treatments

Electrochemical and chemical techniques are extensively employed to fabricate nanostructured, chemically active coatings on titanium surfaces. The procedures encompass anodization, acid etching, alkaline treatment, sol-gel deposition, and chemical vapor deposition (CVD). Together, they can augment surface roughness, alter wettability, improve corrosion resistance, and foster robust integrative interactions with adjacent tissues [49].

Anodization, or anodic oxidation, is a well-established and adaptable method employed to alter the roughness and topographical characteristics of titanium implant surfaces. By modifying process parameters including oxidation duration, applied voltage, electrolyte composition, and electrolyte concentration, one can achieve precisely controlled oxide architectures, varying from dense layers to nanoporous and nanotubular TiO_2 structures.

Anodization results in the formation of an oxide layer at the metal–electrolyte interface through field-assisted oxidation and partial dissolution, producing an anodic film capable of incorporating electrolyte species. Research utilizing animal models (canines and rabbits) has demonstrated that anodized surfaces have enhanced bone–implant contact and superior biomechanical fixation relative to machining surfaces. The arrangement of gingival fibroblasts along anodically created nanopores offers significant mechanostimulation for soft tissue repair. SEM analysis demonstrates porous TiO_2 layers featuring uniformly distributed pores under 100 nm, suggesting that converting a metallic interface into a nanostructured porous surface is an effective approach to enhance compatibility with surrounding bone and physiological environments while maintaining bulk mechanical integrity [50].

Acid etching is frequently utilized to amplify grain boundaries and improve micro-scale and nano-scale roughness. The process is affected by variables like implant density, surface microstructure, pollution, kind of acid, and duration of exposure. Etched surfaces generally have roughness values (Sa) between 300 and 1000 nm, correlating with enhanced osteoconductivity. The surface layer created post-etching may consist of a thin Ti hydride layer, which is then oxidized to yield TiO_2 features with sizes ranging from 20 to 100 nm and thicknesses approximately 10 nm. These nanometric oxides facilitate the deposition of newly synthesized bone on the implant surface and along the endosteal bone [51, 52].

The combination of sandblasting and acid etching yields surfaces that exhibit markedly improved bone anchoring relative to just machined implants, as seen by elevated torque values at the bone–implant interface. Surface treatments utilizing H_2O_2/HCl followed by heat processing can enhance the adsorption of sticky peptides, whereas micro/nanostructured Ti surfaces treated with H_2O_2 produce reactive oxygen species that augment wettability, cellular spreading, and gene expression. HF treatments produce distinct TiO_2 nanostructures but may induce intricate chemical alterations that necessitate thorough assessment [51, 52].

Alkaline therapy is a commonly employed surface modification technique in dentistry. In vitro experiments demonstrate that alkali-treated titanium surfaces can promote apatite production when submerged in simulated bodily fluid (SBF), indicating bioactivity. Following an alkaline treatment, nanostructured titanium surfaces can be transformed into sodium titanate gels, and further exposure to hydrogen peroxide facilitates the development of titanium-based gels. The deposition of hydroxyapatite (HA) on these pre-treated surfaces results in the formation of continuous bioactive layers on dental implants.

Alkaline treatment facilitates the development of a nanodimensional sodium titanate layer that exhibits significant bioactivity. Activated Na^+ ions engage in ion-exchange processes, resulting in the formation of Ti–OH groups on the surface. In SBF, Ti–OH groups interact with Ca^{2+} ions to form calcium titanates, serving as nucleation sites for calcium phosphate crystallization. The resultant apatite layer contains cations analogous to those in the underlying titanate, establishing a chemically linked contact that promotes osteoblast development and bone formation. Surfaces subjected to acidic or alkaline treatments typically exhibit more significant osteogenic responses compared to untreated titanium or titanium alloy implants [53].

Wet-chemical sol–gel methods provide straightforward and controllable approaches for applying nanostructured coatings on intricate three-dimensional implants. A significant benefit is the capacity to uniformly apply thin, bioactive coatings to porous or threaded surfaces. Classical biomimetic coatings, specifically calcium phosphate-based layers, can be generated through extended immersion (14–28 days) in simulated body fluid (SBF). These biomimetically synthesized, calcium-deficient apatite coatings, typically rough and porous, enhance cell adhesion and facilitate bone tissue regeneration.

In vitro studies indicate that osteoblast cultures on sol–gel-sprayed hydroxyapatite coatings demonstrate superior cell proliferation relative to plasma-sprayed hydroxyapatite surfaces [54]. Sol–gel methods often encompass dip-coating, spin-coating, or spraying precursor solutions onto the implant, succeeded by drying and thermal treatment to create nanoscale thin films formed from the gel [55]. These coatings can be designed to regulate degradation rate, ion release, and mechanical integrity, thus customizing the biological response.

Chemical vapor deposition (CVD) is an effective method for generating conformal, adhering thin coatings on metallic substrates using gas-phase processes. Conversely, physical vapor deposition (PVD) depends on plasma-assisted vaporization. CVD has been utilized to deposit graphene (Gp) onto copper foils and, consequently, on implant materials. Gittens et colleagues. found that graphene-coated surfaces facilitate superior adherence of dental pulp stem cells without requiring osteogenic medium or pharmacological inducers [56]. The increased production of mineralized matrix in the experimental groups indicates that graphene can inherently stimulate osteogenic development.

CVD has been utilized to coat titanium dental implants with diamond nanoparticles, resulting in surfaces characterized by enhanced hardness, superior wear resistance, and improved adhesion. Moreover, CVD-derived nano-ceramic bioactive coatings, including calcium phosphate layers on titanium implants, augment osteoconduction while enhancing abrasion resistance and biomolecule adhesion [57-59]. Metal-ceramic CVD coatings enhance design flexibility by combining mechanical strength with customized biological functioning.

Bioactive and functional coatings

Bioactive and functional coatings serve as a crucial approach to convert titanium from a predominantly bio-inert structural material into an active contributor to bone repair and regeneration. Calcium phosphate (CaP) and hydroxyapatite (HA) coatings are notably efficacious in this context. When utilized on titanium implant surfaces through electrochemical deposition, plasma spraying, sol–gel processing, or chemical vapor deposition, these coatings establish osteoconductive interfaces that nearly resemble the mineral phase of real bone.

Following implantation, CaP coatings undergo partial dissolution in the peri-implant area, resulting in elevated local ionic strength and supersaturation with apatite. This induces the deposition of a nanocrystalline biological apatite layer on the implant surface. Proteins swiftly adhere to this layer, subsequently leading to the attachment and differentiation of osteoprogenitor cells, which generate the extracellular matrix of bone tissue [59]. The resultant bioactive contact markedly enhances osteointegration and augments long-term mechanical stability.

Besides CaP and HA, additional bioactive constituents can be included into coating structures. Nanocomposite surfaces incorporating bioactive glass, polymers like PLGA, or metallic nanoparticles (e.g., silver, zinc, or gold) can deliver synergistic antibacterial, osteogenic, and anti-inflammatory properties. Nanocomposite Ti–gelatin–gold coatings and nanocarbonate-enriched layers have demonstrated the ability to boost cell adhesion, facilitate mineralized matrix formation, and improve the biological sealing of dental implants [60, 61].

Nanoscale surface texturing, electrochemical and chemical treatments, and bioactive coatings collectively provide synergistic methods for enhancing the surface characteristics of titanium-based implants. By amalgamating these methodologies with sophisticated alloy and microstructural design, next-generation implants can attain enhanced biofunctional performance, including expedited osteointegration, superior mechanical compatibility, and sustained clinical success.

Combined Optimization of Composition, Microstructure, and Surface Properties

The adjustment of compositions, microstructures, and surface characteristics of titanium alloys has become crucial in biomedical applications, especially for improving biofunctional features including osseointegration, wear resistance, and corrosion resistance. Recent improvements in surface treatment techniques have demonstrated encouraging outcomes in enhancing the biocompatibility and overall efficacy of titanium-based implants.

Microarc oxidation (MAO) is a highly effective process that generates bioactive layers on titanium alloys via electrochemical oxidation, producing porous surface patterns that improve osseointegration relative to pure titanium implants [62]. The MAO technique is recognized for its capacity to produce ceramic oxides that enhance corrosion resistance and facilitate the integration of bioactive materials, hence improving the biological efficacy of the implant [63]. Furthermore, sol-gel coatings have been investigated for Ti6Al4V alloys, enhancing surface characteristics pertinent to biocorrosion and bioreactivity, while also facilitating customized surface shape [63].

Oxynitriding methods have been employed to augment surface hardness and wear resistance by creating a nitride layer that acts as a protective barrier against wear and biological reactions, thus enhancing the durability of implants in physiological environments [64]. This approach seeks to enhance the mechanical and tribological characteristics while preserving the integrity of the underlying alloy [65]. Plasma nitriding has been demonstrated to improve wear resistance by producing titanium nitrides; nevertheless, it necessitates meticulous temperature control to prevent adverse microstructural alterations (Fig. X).

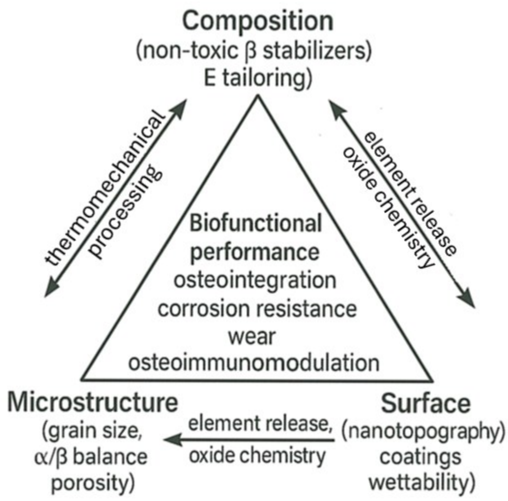

Fig. 1. Integrated design for titanium alloy optimization

Recent studies demonstrate that the integration of nanoscale features onto titanium alloy surfaces markedly affects biofunctional characteristics. For example, employing laser microtexturing or developing nanostructured coatings has been shown to improve the mechanical interlock between the implant and bone, while also fostering biological responses that facilitate osseointegration [66]. The surface wettability of titanium alloys is an essential factor affecting cellular behaviors, where optimum roughness and chemical properties enhance the adhesion and proliferation of osteogenic cells.

Innovative methodologies, including the use of composite surface layers and friction-stir nitriding, have been explored to attain multifunctional characteristics in titanium alloys. The composite coatings are engineered to improve mechanical strength and biological functionality, rendering them more appropriate for bone implants [41]. A thorough examination of these surface modification techniques reveals numerous possibilities for improving the biofunctional properties of titanium alloys, suggesting a trend towards customizing surface characteristics through sophisticated engineering strategies [12, 67].

The implementation of these technologies has led to substantial enhancements in the efficacy of titanium implants, rendering them progressively suitable for load-bearing applications in medical settings. As research advances in this field, a multidimensional strategy that incorporates both surface engineering and alloy composition will be crucial for the development of next-generation biomedical implants [68].

Conclusions

The continuous evolution of titanium-based biomaterials demonstrates that truly high-performance implants can only be obtained when composition, microstructure, and surface properties are optimized in an integrated manner. Alloy design based on non-toxic β-stabilizing elements such as Nb, Ta, Zr, Mo, and Sn has enabled the development of new titanium systems with reduced elastic modulus, enhanced corrosion resistance, and improved mechanical compatibility with human bone. These advances directly address the long-standing challenge of stress shielding and the associated risk of implant loosening.

Thermomechanical processing—through controlled heat treatments, severe plastic deformation, hot forging, and rolling—plays a central role in tailoring grain size, phase stability, and defect structure. By refining and stabilizing the α and β phases at multiple length scales, these treatments produce microstructures that combine high strength, sufficient ductility, superior fatigue performance, and adjustable stiffness. Such characteristics are essential for long-term reliability in load-bearing orthopedic and dental applications.

At the same time, the biological success of any implant is determined at the surface. Advanced surface modification strategies—including anodization, acid and alkaline treatments, sol–gel deposition, and chemical vapor deposition—enable precise control over nano- and microscale topography, wettability, and chemical reactivity. These engineered surfaces promote rapid osteoblast adhesion, accelerated formation of biological apatite, improved antimicrobial resistance, and enhanced biocompatibility, while reducing inflammatory responses and fibrous encapsulation.

Taken together, the synergy among optimized chemistry, refined microstructure, and biofunctional surfaces results in next-generation titanium implants with multifunctional performance. These materials achieve a balance between mechanical robustness, biological integration, and chemical stability, ensuring predictable clinical outcomes and long-term safety. The integrated design philosophy outlined in this work reflects a paradigm shift in the development of metallic biomaterials—from simple load-bearing components to biologically intelligent systems capable of interacting constructively with the human body.

Future research will continue to focus on multiscale engineering approaches, predictive computational design, and the incorporation of smart surface functionalities, paving the way for even more effective and personalized biomedical implant solutions.

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