

Review Article

Metallic Biomaterials for Dental Implants and Implant-Supported Prosthetic Components: A Narrative Review

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Abstract

The use of metallic biomaterials is still central to dental implantology and implant-supported prosthetic rehabilitation due to their mechanical stability, corrosion resistance and biological compatibility with the long-term utility in the oral environment. This narrative review critically evaluates the metallic material in dental implant fixtures, abutments and implant-supported prosthetic components with references to commercially pure titanium, titanium alloys, cobalt-chromium alloys, stainless steels, nickel-titanium alloys and noble and high-noble dental alloys. The review explores the key specifications that are relevant in the selection of materials such as biocompatibility, elastic modulus, strength, fatigue resistance, wear and corrosion behavior, osseointegration potential and clinical performance. The role of alloy composition, surface chemistry, implant geometry and strategies of surface modification in bone-implant interaction and long-term stability are given special consideration. Other issues such as stress shielding, release of metal ions, tribocorrosion, implant abutment interface degradation, allergic reactions, infection related complications, and variability in factors depending on the patients are also identified in the review. Moreover, improved technologies in manufacturing, particularly CAD/CAM and additive manufacturing are also mentioned as the potential solutions to make patient-specific implantation and porous structures with enhanced biomechanical compatibility. In general, the development of the successful clinical implementation of metallic biomaterials in dentistry needs a combination of materials science and surface engineering, implant design, and biological response. The next generation ought to be tailored metallic systems with refined mechanical behavior, controlled surface reactivity, enhanced corrosion resistance, and standardized long-term biological/clinical validation



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1. INTRODUCTION

Dental alloys are valuable materials in restorative dentistry, prosthodontics, orthodontics, and the construction of dental implants [1, 2]. For many years, dental implants have been used to support prosthetic rehabilitation; long-term success is based on factors like implant design, material selection, and biological integration [3]. The various components of dental implant systems, such as fixtures, abutments, prosthetic screws, and implant-supported superstructures, play crucial roles in restoring missing teeth and facilitating oral function. However, dental implants have functional limitations in addition to their benefits. Challenges facing implant materials include limited lifespan, concerns about biocompatibility, corrosion, wear debris, inflammatory responses, and potential damage to adjacent tissues [4, 5]. Thus, selecting the appropriate biomaterials for the design and manufacture of implants is essential. Commercially pure titanium and titanium alloys are the main materials used for dental implant fixtures. Co-Cr alloys are mostly used for prosthetic frameworks. In addition, stainless steel and NiTi alloys are used in limited or specialized dental applications because of their superior mechanical properties, corrosion resistance, and fatigue resistance. These metallic materials form key biomaterial systems for dental implant components. However, their clinical application depends on the specific component and the conditions to which it is exposed [6]. In dentistry, the use of pure metals has been limited to gold foil and platinum foil, as alloys proved superior due to the inadequate mechanical properties of pure metals in fixed prosthetic limbs. Alloys are systems of metallic materials consisting of two or more elements, usually metals; they may include minor non-metallic additives that improve their properties and render the necessary properties for dental restorations. Pure gold has a tensile strength of 130 MPa; for example, when 10 wt.% copper is added, this strength increases to 395 MPa. With, proper elements added and good casting conditions, it can exceed 500 MPa. Additionally, hardness varied from 28 kg/mm² for pure gold to almost 200 kg/mm² for a standard gold-based casting alloy.



Therefore, using alloys ensures essential biological and physical properties for the successful and lasting application of fixed prosthetics [7-9]. Dental casting alloys are conventionally classified into three groups based on their noble metal content: high noble, noble, and predominantly base metal alloys. The base metal alloys are mainly composed of key elements such as Ni, Co, Fe, or Ti with minor alloying additions. Commercially pure titanium is not considered a dental casting alloy in the traditional sense because it is an unalloyed titanium with controlled levels of impurities and interstitial elements according to the specifications of the American Society for Testing and Materials (ASTM) [8,10]. Dental casting alloys have played a significant role in the control of dental diseases. Their use has diminished with the advent of all-ceramic restorations and stronger resin-based composites. However, these alloys still represent the primary material for fixed prosthetic restorations. This trend can be expected to continue since alloys offer an excellent combination of strength, modulus, wear resistance, and biological compatibility, all of which are vital factors to ensure long-term durability in the oral environment [11, 12].

Dental implants have become widely used for replacing missing teeth because they can preserve the alveolar bone, provide long-term function, and support fixed prosthetic rehabilitation. However, their application may be limited by patient-specific and treatment-related factors, including periodontal health, systemic health, treatment cost, jawbone density and quality, and the ability of the surrounding bone to tolerate the mechanical loads transmitted by the implant-supported prosthesis. If bone volume or quality is inadequate, bone grafting may be required before or during implant placement. On the other hand, conventional prosthetic options may be less expensive, time consuming, and surgically less invasive than implant therapy, but they affect adjacent teeth and therefore must be replaced periodically [13-16].

Alloys used in dental applications must be well studied to meet fundamental criteria, including strength, biocompatibility, wear and corrosion resistance, and physical and mechanical reliability, to achieve osseointegration between the implant surface and the surrounding bone and ensure reliable and long-lasting restorations in dental treatments. Peri implant diseases, like peri-implant mucositis and peri-implantitis, can compromise peri-implant tissues and may lead to implant failure within a few years or months. Therefore, ensuring material non-toxicity and supporting bone remodeling are fundamental in case of bone damage to create a suitable environment and long-term sustainability in supporting the implant in terms of functional mechanical load and biological tolerance [17-24]. Numerous studies have investigated the biological, mechanical, and electrochemical properties of dental implant alloys, including corrosion, ion release, fatigue resistance, and hypersensitivity [25-30]. The need to provide high-quality dental care continues to drive research, development, and innovation in dental biomaterials. Therefore, the development of dental materials with lower elastic modulus, improved strength, corrosion resistance, esthetics, and biocompatibility remains a major goal for dentists and materials scientists. Dental alloys still play a major role in the success of modern dentistry despite existing challenges and the emergence of alternative materials driven by continuous advances in dental technology and materials science [29, 31-34]. The contribution of this review lies in its integrated discussion of metallic biomaterials across the complete dental implant-supported rehabilitation system, rather than focusing only on implant fixtures. This review connects alloy composition, biological response, electrochemical behavior, mechanical performance, corrosion and wear resistance, surface modification, implant design, and advanced manufacturing with their clinical implications. Therefore, the purpose of this review is to compile the most recent scientific data on the biological, electrochemical, and mechanical requirements, as well critical challenges related to dental implants and implant-supported prosthetic component design and manufacturing approaches. By evaluating these parameters, this paper establishes a comprehensive framework to assist material scientists and dentists in making evidence-based decisions regarding material selection and implant design to improve long-term clinical outcomes.

2. REVIEW SCOPE AND LITERATURE SELECTION

This narrative reviews a focused and critical overview of metallic biomaterials used in dental implantology, with emphasis on implant fixtures, abutments, implant-supported prosthetic frameworks, surface modification strategies, corrosion and wear behavior, osseointegration, biomechanical compatibility, advanced manufacturing, and clinical performance in the oral environment. The review aimed to integrate evidence from materials science, dental implant design, surface engineering, and clinical dentistry clarify the relationship between alloy composition, surface properties, implant geometry, and biological response. A narrative literature search was performed using main scientific databases, such as Web of Science, Scopus, ScienceDirect, PubMed, Google Scholar, and SpringerLink. The search focused mainly on English-language peer-reviewed articles and reviews, supported where necessary by selected textbooks, handbooks, standards, and authoritative sources relevant to dental biomaterials and implant-related metallic components. The following keywords have been individually or in combination: dental implants, metallic biomaterials, titanium alloys dental implant alloys “stainless steel dental implants, cobalt–chromium alloys, nickel–titanium alloys, implant-supported prostheses osseointegration, corrosion resistance, wear resistance, surface modification, “implant design, “additive manufacturing, and “clinical performance. The included literature publications published between 1980 and 2024, with priority given to recent studies addressing the biological, mechanical, electrochemical, and clinical performance of metallic materials in dental implantology. Sources were selected according to their relevance to implant fixtures, abutments, prosthetic screws, implant-supported frameworks, surface treatments, corrosion and tribocorrosion, osseointegration, advanced manufacturing, and clinical applications. Studies focused only on unrelated non-dental applications, non-metallic restorative materials without implant relevance, or papers lacking clear material, biological, or clinical relevance were not emphasized. Because this a narrative review, formal PRISMA screening, risk-of-bias assessment, and meta-analysis were not performed.

3. REQUIREMENTS AND LIMITATIONS OF METALLIC BIOMATERIALS IMPLANTATION

3.1. Biocompatibility

Biocompatibility in dental implantology indicates the capability of an implant material to perform for its intended function without producing unacceptable local or systemic adverse effects while supporting stable peri-implant tissue healing. For end osseous implants, biocompatibility is not limited to the absence of toxicity. It also includes the ability of the surface to permit protein adsorption, osteoblast attachment, bone formation, and stable osseointegration under functional loading [35, 36]. A clear distinction should be made between bioinert, bioactive, biodegradable, and bio tolerant responses. Titanium and titanium alloys are commonly described as bioinert or highly biocompatible because their passive TiO₂ layer limits corrosion and supports bone contact after appropriate surface modification. Bioactive behavior is usually achieved by adding or forming surface layers, such as calcium-phosphate or hydroxyapatite coatings; hydroxyapatite itself is not a metallic biomaterial but a bioactive ceramic coating that may enhance early bone bonding. Biodegradable metals, like zinc-, magnesium-, and iron-based alloys, are being investigated for some biomedical applications, but they are not routine materials for permanent dental implant fixtures because dental implants require long-term mechanical stability. Bio tolerant materials may be accepted by tissues but can become separated from the bone by fibrous tissue; this response is undesirable for end osseous dental implants where direct bone-implant contact is required [37-41]. Therefore, the biological performance of metallic implant materials depends on alloy chemistry, passive film stability, surface roughness, surface energy, corrosion resistance, and the local peri-implant environment. Metal ion release, wear debris, or corrosion products may contribute to inflammatory responses, hypersensitivity reactions, or loss of peri-implant bone, especially at modular connections such as the implant-abutment interface. For this reason, implant biomaterials should be evaluated using both in vitro tests, such as cytotoxicity and corrosion assays, and in vivo or clinical measures, such as bone-to-implant contact, peri-implant tissue health, marginal bone loss, and long-term survival. (Table 1) shows the biomaterial classes according to their tissue response, with emphasis on their relevance to implant-related applications.

Table (1): Classification of biomaterials according to tissue response [37-43].

Biocompatibility group	Response	Examples	Effect
Bioresorbable/Bio degradable biomaterials	Replaced by the autologous tissue	Magnesium-based, zinc-based, and iron-based alloys	Potentially favorable tissue response when mechanical, biological, and clinical factors are properly controlled.
Bioactive biomaterials	Formation of bone tissue around the implant material with strong integration at the implant surface	Calcium phosphate-based bioactive coatings, including hydroxyapatite (HA)	Potentially favorable tissue response when mechanical, biological, and clinical factors are properly controlled.
Bioinert biomaterials	Support bone contact with minimal chemical interaction; stable osseointegration strongly depends on surface properties and clinical conditions	Ti, Nb, and Ta	Potentially favorable tissue response when mechanical, biological, and clinical factors are properly controlled.
Bio tolerant biomaterials	May lead to fibrous tissue encapsulation and limited direct bone-implant contact; this response is generally undesirable for end osseous dental implant	Co-Cr alloys, stainless steel, almost all synthetic polymers and most metals	Implant rejection leading to failure

Common methods for assessing biocompatibility include in vitro tests for, sensitization, cytotoxicity, hemolysis, irritation, and genotoxicity, as well as in vivo and clinical assessments for Oste conductivity, osseointegration, bone-to-implant contact, peri-implant tissue response, and bone mineral apposition rate. Many machining operations, key surface texture mechanisms, and cold-working techniques influence a metal's biocompatibility, either favorably or unfavorably [44-46]. In the body, biocompatibility is reflected by the effects of an inflammatory response at the tissue-implant interface, corrosion rates of the metal, and metal ion or debris toxicity. When a metal degrades in the body due to wear or corrosion, the released ions and wear debris may become biologically active and may contribute to local inflammation or adverse tissue responses. The exact definition of biocompatibility is constantly evolving and is still a matter of lengthy debate. In the present state, biocompatibility usually describes the "long-term suitability" of a material for contact with body tissues while, being inert or presenting itself in a way that will not produce an immune response, alter the structure of the tissue, or result in foreign body rejection. In this sense, the term "biocompatible" is used as a relative term, defining the amount of hostile response a material may produce concerning the same material or other foreign materials to the body [47-50]. (Table 2) Clinically relevant alloying systems and concerns in dental implant-related components.

Table 2: Clinically relevant alloying systems and concerns in dental implant-related components [9, 42, 43, 47, 51-67].

Element/alloy system	Role in implant-related materials	Main concern to discuss	Implant-related relevance
Ti and TiO ₂ passive film	Base material for most endosseous dental implants.	Passive film damage, tribocorrosion, and ion/debris release under micromovement.	Primary choice for fixtures and many abutments.
Al and V in Ti-6Al-4V	Strengthening elements in a widely used titanium alloy	Potential biological concerns are discussed in the literature; motivate interest in V-free and beta-type Ti alloys	Use cautiously and relate to implant components requiring high strength.
Nb, Ta, Ar, and Mo	Beta stabilizers or biocompatible alloying additions in newer Ti alloys	Need long-term clinical validation and standardized corrosion/fatigue testing	Promising for lower-modulus or improved corrosion-resistant implant alloys
Co-Cr-Mo	High-strength, high-stiffness framework or bar material	Ion release, corrosion behavior, high modulus, and polishing/surface finishing	More relevant to implant-supported frameworks than implant fixtures
Ni-containing alloys	Used in some dental alloys and NiTi components	Nickel hypersensitivity and corrosion concerns	Avoid presenting NiTi as a routine implant fixture material
Stainless steels	Historical/temporary or auxiliary use; not the standard for permanent dental fixtures	Crevice/pitting corrosion and nickel content	Discuss only limited implant-related applications.
A, P, and Pt high-noble/noble alloys	Prosthetic superstructures, restorations, or implant-supported prosthetic components	Cost, mechanical stiffness, casting/CAD-CAM limitations, and galvanic coupling with other metals	Not primary materials for endosseous fixtures

3.2. Physical and Mechanical Properties

Despite the focus on biocompatibility, mechanical properties are equally significant for the long-term clinical success of dental implant materials. The selection and design of metallic biomaterials depend on physical and mechanical properties, such as tensile strength, elastic modulus, elongation, yield strength, hardness, and fatigue resistance. These properties determine the response of the implant and prosthetic components to repeated cyclic loading during mastication. Therefore, appropriate mechanical performance is essential for maintaining long-term function under oral loading conditions. Density is important because it influences the specific strength and specific stiffness of metallic biomaterials. In addition, other properties, like specific heat, melting point, thermal expansion, and thermal conductivity, also play important roles in determining a metal's suitability for particular uses [36, 68]. Failure to consider these requirements may lead to delayed tissue response, bone resorption, impaired osseointegration, or implant failure. The geometry of the implant affects selecting materials based on their mechanical properties. The implant geometry determines how physical stress is distributed at bone-implant interface and within the surrounding bones. It also influences the range of movement and occlusal stability, implant–prosthesis fit, load distribution, and resistance to micromovement, which are crucial for proper articulation [69-71].

When selecting a material for an implant anchored in bone, it is significant to consider the stiffness mismatch between the bone and implant. Biomechanical incompatibility may occur when the implant is too stiff relative to bone or lacks sufficient fatigue strength, increasing the risk of bone resorption, fracture, or loosening [72]. Elastic modulus of bone varies between 4 and 30 GPa, depending on bone type, density, anatomical site, and measurement direction [68, 72, 73]. Therefore, implant materials with a much higher stiffness than bone may reduce physiological stress transfer to the surrounding bone, resulting in stress shielding, peri-implant bone resorption, and eventual implant loosening [74, 75]. In addition to mechanical compatibility, dental implants must maintain surface integrity, corrosion resistance, and mechanical stability in the oral environment, where they are exposed to saliva, microbial biofilms, cyclic loading, and pH fluctuations. Microbial colonization at the implant-soft tissue interface promotes biofilm formation, which accounts for a significant percentage of implant failures in clinical settings [68, 72, 73]. (Table 3) Physicals and mechanical properties of selected dental alloys according to their processing conditions.

Table 3. Mechanical and physical properties of selected dental alloys [9, 53, 68, 76-81].

Dental alloy	Mechanical properties					
	Condition	Elastic modulus, (GPa)	Tensile strength, (MPa)	Yield strength, (MPa)	Fracture elongation %	Density, (g/cm ³)
Stainless steel alloys						
316 Wire	As-received	185-191	2275-2351	1955-2070	2-10	7.95 - 8
316L	Annealed	190-200	550-600	220-331	50-55	7.95
	Cold-worked	167-200	896-1014	790-827	20-25	7.9-7.95
108	Annealed	188	931	586	52	7.63
	Cold-worked	188	1344	1179	35	7.63
Nickel-Chromium alloys						
Ni-Cr-Be	Casting	165-210	778-1355	325-838	3-23.9	7.9-8.1
Ni-Cr	Casting	141-248	539-919	180-858	<1-32.6	7.9-8.7
Cobalt-Chromium alloys						
Co-Cr-Mo	Casting	155-240	655-889	390-644	1.5-10	8.5
Co-Ni-Cr-Mo	Wrought/annealed	232	795-1007	240-655	50-70	9.2
Co-Cr-Ni	Casting	198	685	470	8.0	7.5-8.5
Co-Cr-Ni Wire	As-received	146-198	1515-2000	827-1241	5-15	7.5-8.5
	Stress relieved	179-204	1790-2275	1103-1378	8.0	7.5-8.5
Titanium and its alloys						
CP-Ti	Casting	96-114	240-550	170-480	7.9-20	4.4-4.5
CP-Ti grade 1	Annealed	100-103	240	170	24	4.51
CP-Ti grade 2	Annealed	100-103	345	275	20	4.51
CP-Ti grade 3	Annealed	100-103	450	380	18	4.51
CP-Ti grade 4	Annealed	100-104	550	485	15	4.51
	Cold-worked	110	760-888	485-725	8-12	4.51
Ti-6Al-4V ELI	Annealed	110-116	860-1076	520-896	10-15	4.43-4.5
Ti-6Al-4V	Casting	113-137	877-930	830-870	2.1-12	4.43
Ti-6Al-7Nb	Annealed	105	978-1024	913	10-15	4.52
Ti-15Mo	Annealed/aged	78	874	544	10-15	4.96
Nickel-Titanium alloys						
Ni-Ti wire-A	-	120	527-1380	230-379	13-40	6.45
Ni-Ti wire-M	-	32-50	700-1000	207-552	10-20	6.45
Others						
Pure gold	-	90	130	20	45	19.3
Gold casting	-	90	450-550	207-434	10-39	11.3-15.5

Note: ELI = Extra Low Interstitial

By carefully considering the implant geometry and selecting materials with appropriate mechanical properties to withstand physiological forces and stresses, the aim is to achieve optimal stress distribution to avoid implant loosening and the need for revision surgery and to prevent stress shielding. Materials with a good combination of high strength and low Young's modulus closest to the bone facilitate the transfer of stress to the surrounding bone and ensure a longer service period for the implant in terms of durability and functionality [42].

3.3. Wear and Corrosion Resistance

The oral environment is highly aggressive for metallic implant components because saliva, chloride ions, proteins, microbial biofilms, dietary acids, fluoride exposure, and pH fluctuations can affect passive film stability [82-87]. In dental implantology, corrosion should be discussed together with mechanical wear because implant components are exposed to cyclic loading and micromovement. This combined process, known as trickeration, is particularly relevant at the implant-abutment interface, screw joints, and framework connections [34, 63-66, 83, 87]. Titanium-based implants have been characterized for their corrosion resistance because they possess a stable TiO₂ passive layer. Nevertheless, surface damage, wear, electrochemical interactions with other metals, or low-pH inflammatory processes can compromise the layer and promote ion release [42, 52, 60, 61, 63, 66, 88].

The alloys that require careful consideration are Co-Cr alloys, stainless steel, and Ni-containing alloys because, their decomposition products and ions released could cause localized biological responses or immune sensitization in a person [9, 47, 53-58, 65, 88-91]. In the case of prosthetic elements supported by implants, surface polishing and finishing, alloy selections, and control of galvanic interactions are of foremost importance [63-66, 84, 86, 92-94]. Further studies are needed to evaluate the combined wear-corrosion behavior under conditions simulating the oral environment, such as cyclic mechanical loading, saliva chemical properties, biofilm-induced pH variations, and modular implant interfaces. Use of only static corrosion data cannot be used to predict implant performance in the long term. Hence, to increase the lifespan of the implants and reduce adverse biologic effects, it is necessary to design materials with strong biocompatible oxide surfaces and increased resistance to corrosion and wear.

3.4 Osseointegration

The direct structural and functional linkage between the host bone and biomaterial surface during functional loading is called osseointegration. In metallic-based implant systems, osseointegration depends on the surface's chemical composition, surface topography, surface wetting behavior, durability, and design features of the oxide film and not just the overall alloy strength. Controlled roughened titanium surfaces generally facilitate bone adhesion compared to low-roughness surfaces, but uncontrolled topography or undesirable surface contaminants may promote plaque accumulation and peri-implant soft tissue inflammation. The success of implant integration also depends on bone density, mechanical fixation at placement, tissue trauma, functional loading strategy, oral hygiene, systemic conditions, smoking, and microbial control. Therefore, the selection of implant material should be discussed together with the implant architecture and clinical context. The material may be biocompatible under experimental conditions, but it may fail in vivo if implant micromovement, inadequate bone density, biomechanical overloading, or implant-associated bone loss prevents stable osseous contact [42, 95-104].

3.5 Tailored Functionality

Current market trends in metallic biomaterials for dental applications emphasize the need for patient-tailored materials. Fully customizable dental implants designed according to individual clinical requirements 'A higher vitamin C intake decreased the risk of osteoporosis. by both clinicians and patients for technical and esthetic reasons. Individualized implant design and production techniques may improve surgical outcomes and reduce post-surgical discomfort associated with implant placement. Advances in high-resolution imaging and design software have further supported the customization of metallic biomaterials, enabling implant designs that better match patient-specific anatomical and functional needs. For dental applications, customization mainly focuses on biomechanical and esthetic requirements. From a biomechanical perspective, implant-supported structures can be designed to distribute occlusal forces more effectively, such as by modifying the thickness or geometry of dental bridges to reduce the load on each artificial tooth. From an esthetic perspective, high-resolution imaging has increased the demand for implants that closely match the patient's anterior anatomy, facial symmetry, and coloration. Since facial symmetry and esthetic harmony are highly important in functional and cosmetic restoration, implant shape, micromorphology, and macro-geometry should be adapted to individual patient requirements. Such one-to-one design and fabrication approaches may help achieve optimal clinical outcomes and improve patient acceptance of dental rehabilitation [105-108].

4. CLASSIFICATION OF METALLIC BIOMATERIALS

The American Dental Association (ADA) has classified alloys used in dentistry primarily based on their chemical composition. High-noble alloys contain a high proportion of noble metals, typically 40–88 wt.% gold, with other noble elements such as palladium and platinum included as primary components. Rhodium, ruthenium, osmium, and iridium are also classified as noble metallic elements. Due to the high concentration of gold, palladium, or platinum, these alloys are comparatively costly and are not often used in everyday dental treatment. Nevertheless, when appropriately processed, they typically offer a high level of corrosion resistance, preferable biocompatibility, positive marginal adaptation, and long-term clinical stability. These alloys are relatively dense, with most exceeding 13 g/cm³ compared to other classes of dental alloys. Silver and copper are usually used to enhance hardness and strength. Nevertheless, the higher the palladium or platinum content, the higher the liquidus temperature since the melting point of these metals is higher than that of gold, about 1554 and 1772 Celsius, respectively, as compared to 1065 Celsius in gold.

This higher liquidus temperature can make investing and casting more challenging, although it may also support their use in selected restorative applications. The high noble metal content contributes to stability in the oral cavity, although Au-Pt alloys may release zinc if they are not properly manipulated during laboratory processing. Overall, high-noble alloys are not highly rigid and may be too flexible for large cast restorations. In addition, Au-Ag-Cu alloys are not suitable for some restorative applications because of their relatively low melting range. The properties of gold casting alloys can be adjusted by adding elements such as silver, copper, palladium, platinum, zinc, indium, iridium, and ruthenium. Copper and silver are mainly added to modify color and improve strength and hardness, whereas palladium and platinum improve corrosion resistance, tarnish resistance, and overall alloy stability. Zinc and indium may improve castability by lowering the melting range and acting as scavenging elements during processing. Small additions of grain-refining elements, such as iridium and ruthenium, could further enhance microstructural uniformity and mechanical performance.

Therefore, the final clinical performance of gold-based dental alloys strongly depends on alloy composition, processing conditions, and the balance between mechanical, esthetic, and corrosion-related properties [51, 78, 79, 109-113]. Noble alloys contain a high proportion of noble metals, with palladium content ranging from 42 to 88 wt.%. In alloys that contain gold, its content usually does not exceed 35 wt.%, while copper or silver is present in higher amounts compared with high-noble alloys. These alloys are structurally more diverse than high-noble alloys and may be classified into gold-based, palladium-based, Pd-Cu and Ag-Pd systems. Gold-based noble alloys are relatively low-melting and may have limited suitability for some restorative applications. Palladium-based alloys may contain up to 77 wt.% palladium with little or no gold, while the remaining composition is typically balanced with copper or gallium. Pd-Cu alloys are strong and hard, although they are more difficult to process and generally show lower corrosion resistance than gold-based alloys. Ag-Pd alloys usually contain at least 25 wt.% palladium, which allows them to be classified as noble according to ADA standards. Noble alloys have a moderate density of approximately 10–12 g/cm³, which is lower than that of high-noble alloys. However, their yield strength and hardness are often equal to or greater than those of high-noble alloys, mainly because of their high palladium content.

Their lower cost compared with high-noble alloys also makes them more widely used in dental practice. Pd-Cu and Ag-Pd alloys can be utilized for crowns and fixed partial dentures, without or with ceramic coverings [51, 52, 78, 79, 109-112, 114, 115]. Base metallic alloys contain nickel, cobalt, and titanium as major constituents, along with other elements such as iron, chromium, copper, zinc, tin, molybdenum, niobium, tantalum, aluminum, vanadium, beryllium, manganese, gallium, and silicon. These alloys may contain less than 25 wt.% noble metals or no noble metals at all. They are majorly used in dentistry due to their relatively low cost and density, as well as their high strength and hardness. However, using base metallic alloys, especially nickel- and cobalt-based systems, remains controversial because of their higher corrosion susceptibility and possible biocompatibility concerns. They could be used for crowns, fixed partial dentures without or with ceramic veneers, removable partial dentures, and dental implant substructures. In dentistry, silver is also considered a base metal due to its tendency to corrode in the oral environment, although it is a precious metal in terms of cost. Pure silver is not commonly used in dental applications. Base metallic elements are generally more prone to corrosion than noble metals; therefore, they are often combined with noble elements to improve alloy properties, including strength, stiffness, wear, and corrosion resistance [9, 51, 53, 54, 78, 79, 111, 115].

Titanium and its alloys are widely used metallic materials in dentistry and have become integral parts of dental treatment since the 1960s [59]. Titanium is commonly used in the manufacture of dental implants due to its favorable mechanical properties, including a relatively low modulus of elasticity (≈ 110 GPa), low density (≈ 4.51 g/cm³) and excellent biocompatibility with bone. Commercially pure titanium (CP-Ti) is the most commonly used titanium-based material, and it is available in four grades (1–4), which mainly differ in impurity and oxygen content, resulting in different mechanical properties [60-62]. Due to these unique properties, CP-Ti and its alloys are widely used in dental implants and metal crowns, as shown in (Figure 1).



Figure 1. Titanium and its alloys used in dental implants and crowns [59]

5. DESIGN CONSIDERATIONS

Design considerations for metallic dental implant systems should be linked to the function of each component. For implant fixtures, the main design variables are diameter, length, thread geometry, surface topography, connection type, and macro-geometry, all of which influence primary stability and stress transfer to bone [60, 62, 69-71]. For abutments and prosthetic screws, the design must control preload stability, bending resistance, fatigue life, and the risk of micromovement at the implant-abutment interface. For implant-supported frameworks, the design must provide adequate rigidity while minimizing cantilever-related stress concentration [60, 63-67]. Finite element analysis and computer-aided design can support the optimization of implant geometry and load distribution, but their results should be interpreted with clinical validation. Patient-related variables such as bone density, parafunction, occlusal scheme, hygiene, and systemic health must be considered together with material properties [70, 116-121]. The goal is not simply to select the strongest metal but, to match material properties, surface behavior, and component geometry to the biological and mechanical demands of the individual clinical case.

6. Advanced ProcESSIN AND CLINICAL APPLICATIONS

6.1 Surface Modification and Functionalization

Surface engineering plays a central role in improving the mechanical and biological performance of metallic biomaterials used in dental implantology. Since the initial interaction between the implant and surrounding tissue occurs at the surface, surface characteristics, like chemistry, roughness, wettability, oxide-layer stability, and coating integrity, strongly influence protein adsorption, cell attachment, osseointegration, corrosion resistance, wear behavior, and long-term implant stability [47, 92, 122-128]. Several surface modification methods were developed to enhance the performance of metallic dental implants and implant-supported components. Surface roughening methods, including acid etching, sandblasting, and combined treatments, are commonly used to increase surface area and improve bone-implant contact. Electrochemical techniques, such as anodization, could modify the oxide layer and enhance corrosion resistance, particularly in titanium and titanium-based alloys. Coating techniques, including plasma spraying, sputter deposition, and other thin-film methods, may also be used to deposit bioactive or protective layers on metallic substrates [92-94, 122, 129-131].

Bioactive coatings, especially hydroxyapatite and calcium phosphate-based coatings, are used to enhance bone bonding and accelerate osseointegration. In addition, antibacterial or ion-releasing coatings, such as silver-containing surfaces, have been investigated to reduce microbial colonization and peri-implant infection risk. Protective coatings could enhance wear resistance, decrease metal ion release, and limit tribocorrosion at implant surfaces as well as implant-abutment interfaces. Adhesion strength, coating stability, long-term degradation, and possible biological reactions must be carefully evaluated before clinical use. Overall, surface modification should not be considered separately from implant material selection and design; the success of surface-treated metallic implants depends on achieving a balance between surface roughness, corrosion resistance, mechanical durability, biological compatibility, and resistance to bacterial adhesion.

6.2 Advanced Manufacturing Techniques

Advanced manufacturing technologies have significantly changed the fabrication and design of metallic dental implants and implant-supported prosthetic components. Computer-aided design and computer-aided manufacturing (CAD/CAM), together with additive manufacturing, allow the production of more accurate, reproducible, and patient-specific dental components. These technologies are particularly useful for fabricating customized implants, abutments, surgical guides, crowns, bridges, and implant-supported frameworks [119, 120, 132-137]. Additive manufacturing, also referred to as metal 3D printing, is one of the most promising techniques in modern dental implantology. Unlike conventional casting or machining, additive manufacturing enables the fabrication of complex geometries, internal porous networks, and controlled lattice structures that are difficult to produce by traditional methods. These porous structures may reduce the stiffness mismatch between the implant and bone, improve mechanical interlocking, support bone ingrowth, and help minimize stress shielding.

Treatment planning and accuracy of surgical work are also enhanced with the use of digital workflows. The combination of radiographic imaging, intraoral scanning, virtual implant planning, and computer-guided manufacturing allows designing the implants and surgical guides based on the anatomy of the patient. This can enhance the positioning of the implant, decrease the duration of surgery, minimize unnecessary bone removal, and enhance the predictability of implant supported rehabilitation [30, 120, 121, 138-140]. Nevertheless, despite these benefits, advanced manufacturing requires precise control of processing parameters, surface quality, porosity, residual stresses, microstructure, and after-processing interventions. Hence, before routine usage in dental implant applications, printed metallic parts need sufficient mechanical, electrochemical, biological, and clinical testing.

6.3 Clinical Applications

Metallic biomaterials are currently popular in dentistry because of their fatigue resistance, high strength, corrosion resistance, fracture toughness, wear resistance, and acceptable biocompatibility in the oral environment. They are primarily used as dental implant fixtures, abutments, implant-supported structures, crowns, bridges, removable partial denture structures, orthodontic components, endodontic instruments, and a maxillofacial reconstructive device. The selection of an appropriate alloy is determined by the purpose of use, loading, biological response, corrosion behavior, esthetic needs, cost, and production method [51, 53, 80, 81, 141-144]. The noble and high-noble alloys are primarily used for full-metal and porcelain-fused-to-metal restorations because of their good corrosion resistance and biocompatibility. Alloys of palladium, gold, and platinum may be used in crowns, suspenders, and certain implant-supported components. Their high cost and relatively lower rigidity than base metal alloys can, however, restrict their use in large structures or in clinical situations that are sensitive to costs. Ceramic-metal restorations, removable partial denture structures, and implant-supported prosthetic substructures commonly use base-metal alloys (particularly cobalt-chromium and nickel-chromium alloys).

These alloys offer high strength, high modulus, strong rigidity, and low cost. Nevertheless, alloys containing nickel need to be used with care due to potential allergic reactions, and the use of cobalt-chromium alloys is frequent when the high strength, reasonable corrosion resistance, and reduced cost are demanded [9, 51-54, 78, 79, 109-115]. Titanium and alloys are the most significant dental implant biomaterials. Titanium and titanium-based alloys are commonly employed in the fabrication of implant fixtures, abutments, and implant-supported components because of their low density, appropriate mechanical properties, corrosion resistance, and

high biocompatibility. Titanium is commercially pure and, comes in various grades, primarily differentiated by oxygen and impurity content, which determines strength and ductility.

When increased mechanical strength is needed, titanium alloys, such as Ti-6Al-4V and more recent Ti-based systems, may be employed, although their long-term biological and electrochemical behavior should be taken into consideration [59-62]. Cobalt chromium alloys are also of clinical significance, especially in crowns, bridges, removable partial dentures, and implant-supported structures. Recent research has indicated that alteration of Co-Cr alloy composition with the addition of other elements like tungsten, niobium, molybdenum, iron, or manganese can affect corrosion resistance, passivation behavior, microstructure, and mechanical properties. These results indicate that Co-Cr alloys with appropriate designs could be used as substitutes to more costly noble alloys in specific dental procedures, particularly cases that demand high strength and acceptable levels of corrosion resistance [55-58].

There is no perfect metallic biomaterial that can be used in all dental applications, yet the key to successful clinical application lies in balancing biological safety, mechanical reliability, corrosion and wear resistance, manufacturability, esthetics, and cost. Surface engineering and advanced manufacturing are valuable pathways to producing patient-specific metallic implants and prosthetic systems with enhanced osseointegration, tuned stiffness, decreased ion release, and enhanced long-term clinical outcomes (Table 4).

Table (4) provides an overview of the applications of metallic biomaterials in implantation [51, 53, 80, 81, 141-144].

Component/ application	Preferred material classes	Why used	Main limitation to mention
Endosseous fixture	CP-Ti; Ti alloys	Biocompatibility, passive oxide film, osseointegration, fatigue resistance.	Stress shielding, fatigue fracture in narrow implants, surface-related complications.
Abutment	Ti alloys; CP-Ti; Co-Cr or noble alloys in selected systems	Strength, fit, corrosion resistance, and esthetics/prosthetic compatibility.	Screw loosening, galvanic coupling, and wear at connection.
Prosthetic screw	Ti or manufacturer-specific alloys	Preload stability and fatigue resistance.	Preload loss, fracture, and corrosion at the interface.
Implant-supported framework/bar	Co-Cr; Ti alloys; noble alloys in selected cases	Rigidity, CAD/CAM processability, strength.	Fit accuracy, corrosion/ion release, and high stiffness.
Implant-supported crown/bridge substructure	Co-Cr; Ti; noble/high-noble alloys	Mechanical support and compatibility with veneering and ceramic systems.	Chipping, galvanic effects, cost, laboratory processing.
Component/ application	Preferred material classes	Why used	Main limitation to mention
Endosseous fixture	CP-Ti; Ti alloys	Biocompatibility, passive oxide film, osseointegration, fatigue resistance.	Stress shielding, fatigue fracture in narrow implants, surface-related complications.
Abutment	Ti alloys; CP-Ti; Co-Cr or noble alloys in selected systems	Strength, fit, corrosion resistance, and esthetics/prosthetic compatibility.	Screw loosening, galvanic coupling, and wear at connection.
Prosthetic screw	Ti or manufacturer-specific alloys	Preload stability and fatigue resistance.	Preload loss, fracture, and corrosion at the interface.
Implant-supported framework/bar	Co-Cr; Ti alloys; noble alloys in selected cases	Rigidity, CAD/CAM processability, strength.	Fit accuracy, corrosion/ion release, and high stiffness.
Implant-supported crown/bridge substructure	Co-Cr; Ti; noble/high-noble alloys	Mechanical support and compatibility with veneering and ceramic systems.	Chipping, galvanic effects, cost, laboratory processing.

Grgur et al. [55] investigated the corrosion behavior of nine noble dental alloys containing 27–97.6 wt.% noble elements. Based on chemical composition and stability in the oral environment, the alloys were classified into three groups. The first group included the most stable alloys, containing at least 40 wt.% gold and at least 60 wt.% noble metals, such as platinum and silver. The second group consisted of stable alloys containing 25–60 wt.% noble metals, including gold, silver, palladium, and platinum. The third group included fewer stable alloys with ≤ 25 wt.% noble metal content. Despite these compositional differences, all tested alloys showed high corrosion stability. Another study evaluated ten noble and gold-based alloys containing 56–86 wt.% gold, 1.50–11.40 wt.% platinum, and varying amounts of palladium, iridium, silver, zinc, tin, iron, copper, rhodium, and titanium. Potentiodynamic analysis showed open-circuit potentials ranging from -82.5 to 102.8 mV and breakdown potentials ranging from 566.7 to 1367.5 mV, indicating good corrosion resistance. SEM analysis also revealed only small-diameter corrosion defects, as shown in (Figure 2). Overall, these findings that noble and gold-based dental alloys possess suitable corrosion resistance for clinical dental applications.

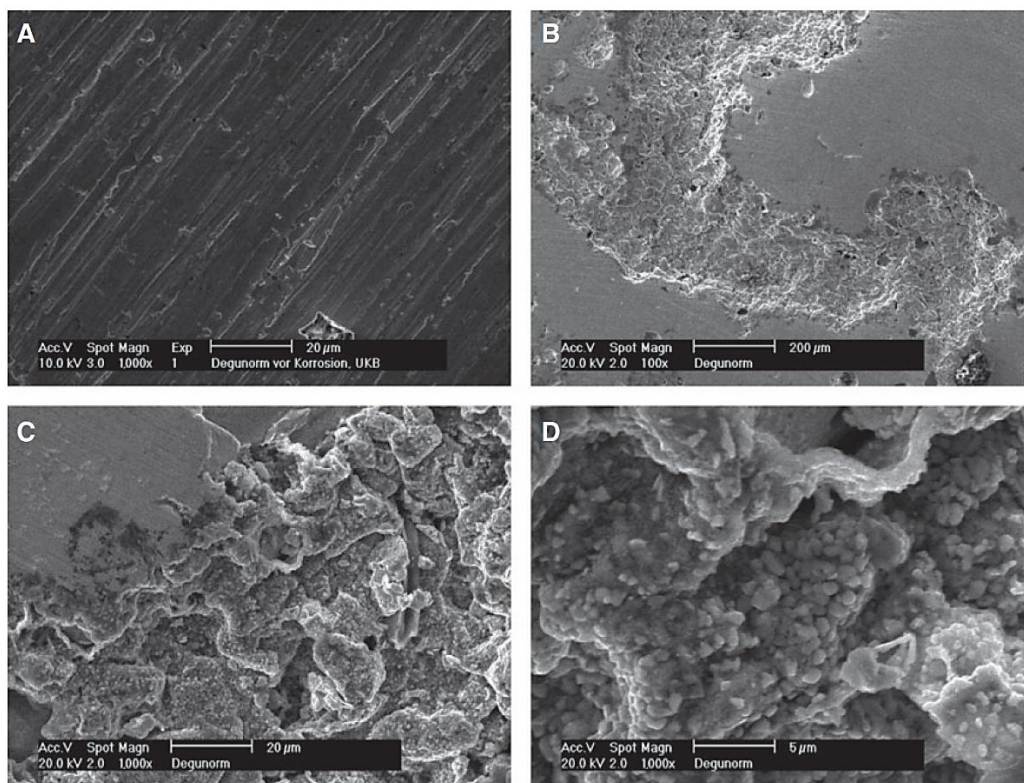


Figure 2. SEM images of samples before and after electrochemical corrosion testing, showing surface changes at different magnifications: (a) before corrosion – at 1000× magnification, (b) after corrosion – at 100× magnification, (c) after corrosion – at 1000× magnification and (d) after corrosion – at 4000× magnification [145].

Microstructural optimization through targeted compositional adjustment and heat treatment was demonstrated by Uriciuc *et al.* [56] in their evaluation of modified Co-Cr dental alloys. Their findings showed that enriching the base matrix with tungsten (W) and iron (Fe), followed by sequential thermal processing, promoted phase transformation through the dissolution of the brittle hexagonal phase and the formation of stable crystalline oxide phases, including Fe_2O_3 , Cr_2O_3 and CoMnO_3 .

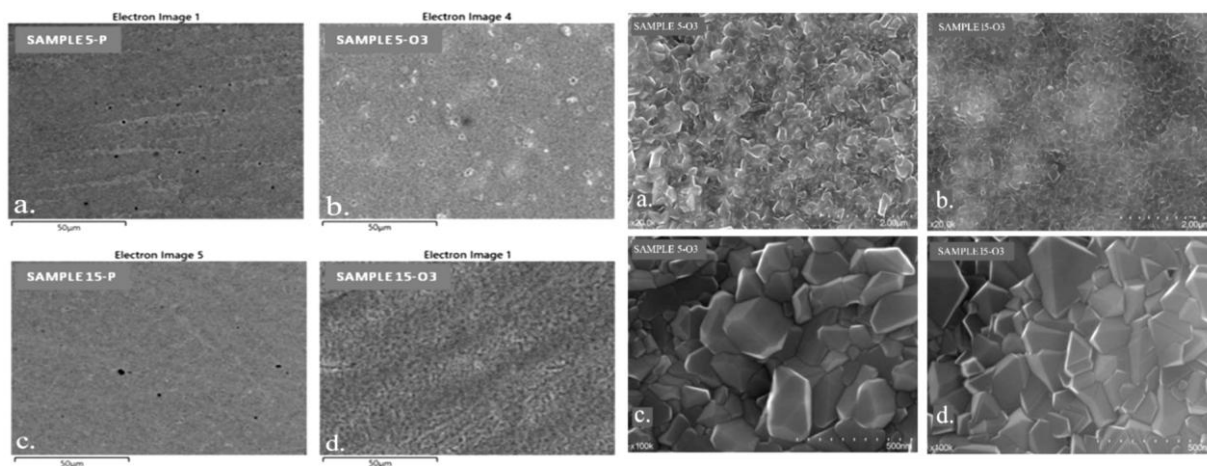


Figure 3. SEM micrographs of heat-treated Co-Cr dental alloys with different W contents (5–15 wt.%). Section A shows the surface morphology after successive heat-treatment cycles (a-d), while Section B highlights the microstructural transition from heterogeneous grains in 5-O₃ (a and c) to a more homogeneous structure in 15-O₃ (b and d) [56]

As shown in the SEM micrographs in (Figure 3), increasing the tungsten content from 5 wt.% in sample 5-O₃ to 15 wt.% in sample 15-O₃ changed the alloy morphology from an irregular heterogeneous polycrystalline structure to a more uniform and homogeneous grain structure. This microstructural refinement improved the electrochemical stability of the alloy and reduced corrosion susceptibility in the aggressive oral environment. Therefore, Co-Cr alloys optimized by W/Fe enrichment and heat treatment may represent durable candidates for long-span crowns, bridge frameworks, and partial denture bases. The effect of alloying elements such as Mo, Fe, W, V, C, N, Ni, Nb, and Mn on the mechanical properties of Co-Cr dental alloys was investigated by Fratila *et al.* [57]. The study alloys showed acceptable mechanical properties, good passivation behavior, and corrosion resistance. The highest recorded elastic modulus was 175 GPa, which is lower than the typical range reported for Co-based alloys, approximately 210–253 GPa. This reduction was attributed to the specific chemical composition of the investigated alloys.

These findings that such alloys may be clinically suitable for fixed and removable dental prostheses, particularly in components requiring relative elasticity and moderate strength, such as abutments, crowns, bridges, and denture frameworks. Jiménez -Marcos *et al.* [58] also reported the clinical potential of transition metal modification when they studied the effects of microalloying a Co-based matrix of 3 wt.% tungsten (W) and 4 wt.% niobium (Nb). Structural characterization showed a stable biphasic crystalline matrix with an instant inclination to passivate when in contact with physiological fluids. The development of a dense passive layer helped in stable electrochemical performance as well as high corrosion resistance, and mechanical tests ensured sufficient structural integrity under three-point bending conditions. As can be seen in (Figure 4), stable biphasic morphology as well as chemically inert surface have been related to limited tissue reactivity and good biological compatibility. Thus, W- and Nb-reinforced Co-based alloys could represent cost-effective alternatives to noble dental alloys for high-stress prosthetic applications, such as implant abutments and fixed substructure frameworks.

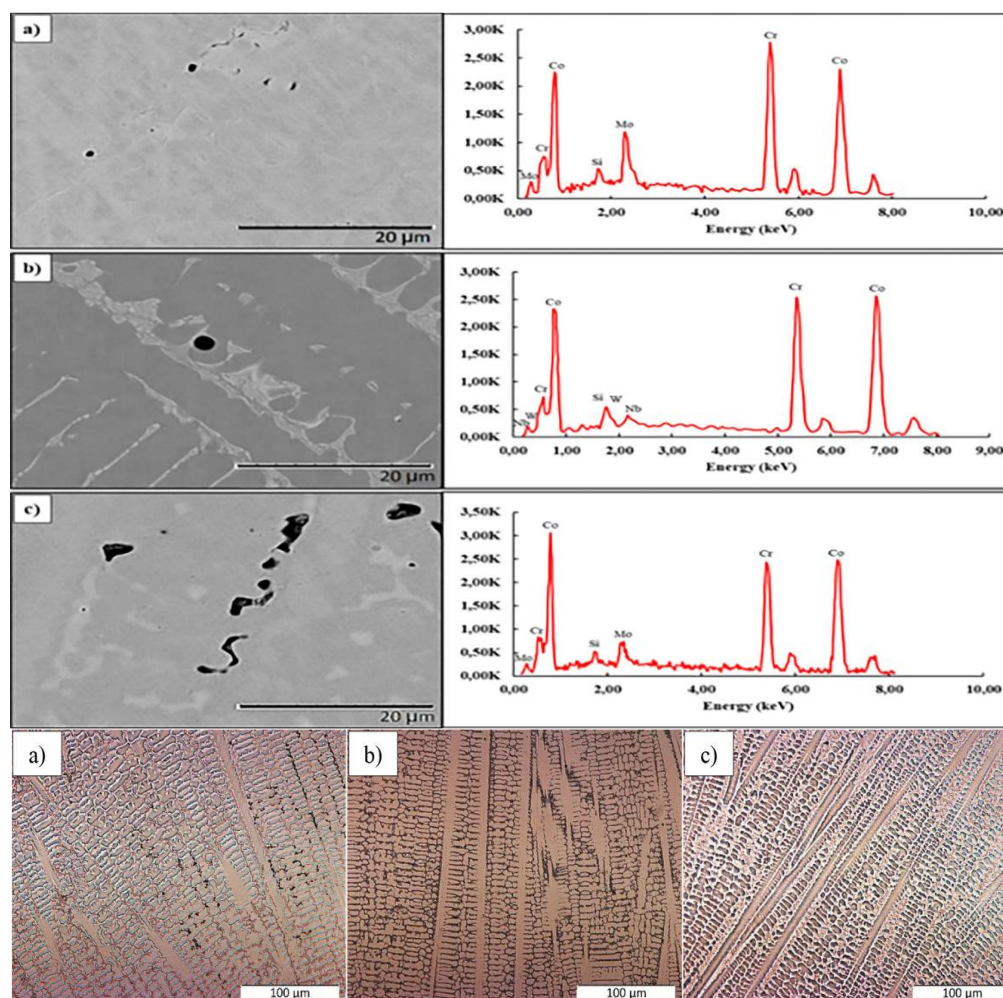


Figure 4. Microstructural and elemental characterization of W and Nb-modified Co-based dental alloys using SEM, EDS, and optical microscopy [58].

7. CHALLENGES and FUTURE PERSPECTIVES

Although metallic biomaterials have been successfully used in dental implantology, many biological, mechanical, electrochemical, and clinical challenges continue to limit their long-term effectiveness. Metal ion release, wear debris, allergic reactions, inflammatory responses, and problems related to infections can result in biological complications. Titanium and its alloys are acceptable because of their positive biocompatibility and corrosion properties, but other metallic systems must be considered carefully, particularly those that incorporate elements linked to hypersensitivity or cytotoxicity issues [47, 88-91, 107, 146]. Biomechanical and mechanical complications are also significant factors that cause the failure of implants. These include implant or abutment fracture, screw loosening, fatigue damage, too much stiffness mismatch of the implant and bone, and stress shielding. Moreover, crevice corrosion and tribocorrosion of the implant abutment interface can increase the rate of metal degradation, decreasing implant stability and longevity. Poor oral hygiene, decreased bone quality, systemic illnesses, smoking, parafunctional habits, and uncontrolled occlusal loading, which are patient-related factors, can further predispose the development of complications [63-67]. The future developments should be in designing some metallic biomaterials, which are patient specific, mechanically compatible, corrosion resistant, and biologically stable. Nickel-free systems, low-modulus titanium alloys, improved cobalt-chromium alloys, and surface-engineered metals could be used to decrease stress shielding, ion release, and adverse tissue reactions.

More sophisticated surface treatments, bioactive and antibacterial coatings, and controlled surface roughness should be streamlined to improve the process of osseointegration and reduce bacteria adhesion and peri-

implant infection. CAD/CAM and additive manufacturing are digital manufacturing technologies that can provide valuable opportunities in the development of implants. Such methods have the capability to yield customized implants, abutments, surgical guides, and porous metallic structures that match the patient's bone quality and anatomy. Controlled porosity as well as lattice structures can enhance bone ingrowth and minimize stiffness discrepancy, though their fatigue resistance, corrosion, and long-term clinical safety should be thoroughly verified. In general, materials science, surface engineering, digital design, biomechanics, and clinical dentistry should be included in future research. Before routine clinical applications, standardized in vitro testing, animal studies, long-term clinical trials, and computational modeling are required to determine the safety and effectiveness of the new metallic biomaterials developed.

4. CONCLUSIONS

The metallic biomaterials continue to play a significant role in dental implantology and implant-supported prosthesis rehabilitation because of their strengths, corrosion resistance, fatigue resistance, and biocompatibility in the oral environment. Commercially pure titanium and titanium alloys are the most commonly utilized dental implant fixtures, while stainless steels, cobalt chromium alloys, nickel titanium alloys, and noble alloys still play crucial roles in prosthetic and implant-supported components. It is important to note that stainless steels, nickel-titanium alloys, and noble or high-noble alloys are not typically thought of as routine materials to use as permanent end osseous implant fixtures; instead, their relevance is majorly related to prosthetic, auxiliary, or selected implant-supported parts, based on the clinical indication, design requirements, and loading conditions. Clinical success of metallic biomaterials relies on achieving the right balance of alloy composition, mechanical behavior, surface properties, implant design, manufacturing method and patient factors. The surface modification and high-technology manufacturing processes have enhanced the fabrication of customized implants and prosthetic components with better biomechanical compatibility and increased osseointegration. No single metallic material fits all dental uses; therefore, continued development regarding optimized alloys, stable surface treatments, and patient-specific implant designs could enhance clinical outcomes. Long-term biological, mechanical, electrochemical, and clinical validation remain important for ensuring reliable and safe use of such materials in dental practice.

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