International Journal of Materials Science and Applications
2026, Vol. 15, No. 3, pp. 100–112
https://doi.org/10.11648/j.ijmsa.20261503.13

Review Article

Titanium, Stainless Steel and Cobalt-chromium-based Alloys: Classification and Diverse Applications

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Abstract

Titanium, stainless steel, and cobalt-chromium-based alloys represent the most widely used metallic biomaterials and high-performance structural materials owing to their outstanding corrosion resistance, mechanical properties, biocompatibility, and strength-to-weight ratio. This review provides a comprehensive classification of these alloys based on chemical composition and thermomechanical processing. Titanium alloys are categorized into α, near-α, α+β, metastable β, and stable β types; stainless steels into austenitic, ferritic, martensitic, duplex, and precipitation-hardened grades; while cobalt-chromium alloys are differentiated into cast (e.g., F75) and forged (e.g., F799) variants. The microstructure property relationships, influence of key alloying elements, and the effects of cold rolling and deformation processing on strength, fatigue resistance, and corrosion behavior are critically examined. Particular emphasis is placed on their diverse applications in the aerospace industry (airframe structures, jet engines, fasteners, and spacecraft components) and biomedical fields (orthopedic implants, cardiovascular devices, dental prosthetics, and trauma fixation devices). Advantages, limitations, biocompatibility issues (such as stress shielding and ion release), and recent advancements in surface modification techniques are discussed. Finally, future directions including the development of low-modulus β-titanium alloys, nickel-free stainless steels, improved Co-Cr alloys, and advanced additive manufacturing routes are outlined to address current challenges and meet the evolving demands of high-performance engineering and long-term biomedical applications.

Keywords

Titanium Alloys, Stainless Steel, Cobalt-chromium Alloys, Classification, Biomedical Implants, Aerospace Applications, Corrosion Resistance

1. Introduction

Titanium, a lightweight, exceptionally strong, and highly corrosion-resistant metal, has served as a cornerstone material across diverse industries for more than two centuries, ever since its elemental discovery in 1791 by the British clergyman and mineralogist William Gregor in black sand deposits from Cornwall, England [1-3].

The development of Ti-6Al-4V, one of its most popular alloys, occurred in the 1940s [4, 5]. Renowned for its exceptional properties, including high corrosion resistance, outstanding strength-to-weight ratio, and excellent biocompatibility [6, 7] titanium and its

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Received: 13 April 2026; **Accepted:** 3 May 2026; **Published:** 18 May 2026

alloys have found widespread applications across diverse sectors, including aerospace [8], medical [9], chemical processing [10], offshore and marine engineering [11, 12], power generation [13], transportation [14], architecture, and consumer goods [15-17].

With a density approximately 60% lower than that of steel and superalloys, titanium exhibits exceptional lightweight characteristics [18, 19]. In addition to their outstanding corrosion resistance, titanium and its alloys exhibit exceptional properties, including high fracture toughness, excellent high-temperature strength, and an impressive strength-to-weight ratio [20, 21]. Titanium alloys, despite being approximately 45% lighter than conventional low-carbon steels, possess superior strength. Although they are about 60% heavier than soft aluminium alloys, they offer nearly twice the strength [22, 23]. Substantial improvements in strength can be achieved through alloying and deformation processing [22, 24]. Titanium alloys possess unique properties, including exceptional mechanical performance, excellent corrosion resistance, low density, and high biocompatibility. Alloying titanium with selected metallic elements further enhances its biocompatibility, making these alloys widely used in the manufacture of biomedical implants [25-27].

Titanium alloys exhibit α, α+β, and β crystal structures, with β-phase alloys showing a low Young's modulus close to that of natural bone, making them suitable for hard-tissue replacement with reduced risk of toxic element release [25-27].

Elements commonly present in titanium alloys, such as tantalum (Ta), niobium (Nb), and zirconium (Zr), are considered biocompatible and contribute significantly to the mechanical strength of biomedical implants [28, 29]. Ti-6Al-4V alloy remains the most recommended material in the biomedical field and accounts for about 45% of implant production [30, 31]. Although its elastic modulus is higher than that of natural bone (55–110 GPa), it still helps reduce the stress-shielding effect compared to other materials [32, 33].

Stainless steel, on the other hand, may be defined as an alloy steel containing at least 12% chromium with or without nickel [34, 35]. Its corrosion resistance is attributed to the formation of a passive oxide film on its surface [36, 37]. Passivity arises from this thin, protective oxide film, which allows the metal to exhibit negligible corrosion despite its inherent tendency to react with the environment [38, 39]. Severe corrosion occurs when the passive film breaks down, leading to localized attack such as pitting, crevice corrosion, intergranular corrosion, and stress corrosion cracking (SCC) [40, 41].

The popularity of stainless steel has increased significantly over the past decades. Global stainless steel production rose from 35.9 million tonnes in 2012 to 48.2 million tonnes in 2017. Stainless steel 316L is widely recommended for biomedical applications due to its favourable mechanical properties and relatively low manufacturing cost [42, 43]. SS 316L contains approximately 10.5% chromium, which forms a protective chromium oxide layer on the surface, significantly enhancing its corrosion resistance [44]. Moreover, SS 316L contains additional elements such as iron, nickel, and carbon. The low carbon content (approximately 0.03%) enhances yield strength while improving corrosion resistance, making the alloy suitable for orthopedic applications [45]. Duplex steel is also preferred for implant applications when its surface is modified using specific surface modification techniques, which enhance the longevity and performance of the implant in biomedical applications [46].

Cobalt–chromium (Co–Cr) alloys are widely used in load-bearing applications such as hip and knee joints due to their high hardness and excellent tribological properties. Furthermore, clinical studies have demonstrated that Co–Cr alloys exhibit good biocompatibility [47-49].

In Co–Cr alloys, chromium constitutes approximately 28 wt%, molybdenum about 6 wt%, with cobalt forming the balance. These alloys interact with cells and protein solutions within the human body. The presence of 28 wt% chromium promotes the formation of a stable Cr_2O_3 oxide layer on the material surface, which protects against corrosive environments while enhancing biocompatibility and improving osseointegration [50, 51].

In this article, we delve into the classification of titanium, stainless steel, and cobalt-chromium-based alloys, which is determined by both chemical composition and thermomechanical processing. In addition, we explore their diverse applications in detail, highlighting key examples, advantages, limitations, and microstructure–property relationships.

2. Classification of Titanium, Stainless Steel and Cobalt-chromium-based Alloys

Titanium is available in both commercially pure forms and as alloys. Elemental (commercially pure) titanium exhibits low thermal conductivity, relatively low density and elastic modulus, moderate strength, excellent corrosion resistance in diverse environments, and high chemical reactivity with various elements [14, 15]. The microstructure and properties of titanium alloys are strongly influenced by chemical composition and thermomechanical processing. At low temperatures, pure titanium exhibits a hexagonal close-packed (hcp) crystal structure, commonly referred to as α-titanium [52, 53]. At elevated temperatures, it transforms into a body-centered cubic (bcc) structure known as β-titanium. The β-transus temperature for pure titanium is approximately 882°C, although this value varies depending on alloying elements and impurities [54, 55].

The coexistence of these two crystal structures underpins the wide range of properties exhibited by titanium alloys [56]. Alloying elements are classified as neutral, α-stabilizers, or β-stabilizers based on their influence on the stability of the α or β phases [57]. Neutral elements have little to no effect on the β-transus temperature. β-stabilizing elements are further classified into β-isomorphous and β-eutectoid elements [58].

The former promotes β-phase stability across all alloy compositions, whereas the latter induces eutectoid transformations of the β phase. Aluminium is the primary α-stabilizing element, while molybdenum is among the most effective β-stabilizers. The stabilizing effects of α-stabilizers are commonly quantified using aluminium equivalence, while molybdenum equivalence is used to assess the influence of β-stabilizers [4, 59, 60].

Table 1. *Physical properties of titanium and other selected contestant materials [59, 61].*

Properties	**Ti**	**Al**	**Ni**	**Fe**
Density, g/cm^3	4.5	2.7	8.9	7.9
Melting point, °C	1670	660	660	1538
Thermal conductivity, W/mK	15–22	221–247	72–92	68–80
Elastic modulus, GPa	115	72	200	215
Reactivity with oxygen	High	High	Low	Low
Corrosion resistance	High	High	Medium	Low
Cost	High	High	High	Low

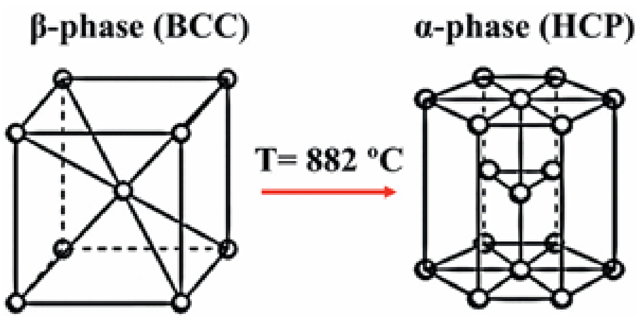

Figure 1. *Crystalline Structure and Phase Transformations of Elemental Titanium [62, 63].*

Based on their metallurgical structures, titanium-based alloys are classified into three main groups: alpha (α), alpha-beta (α–β), and beta (β) alloys. Additionally, they can be further subdivided into near-alpha and metastable beta alloys [64].

Alpha alloys consist predominantly of the α-phase and include both commercially pure titanium and alloys containing α-stabilizers such as aluminum and tin. These alloys are widely used in aerospace applications due to their favorable combination of strength and formability. [64, 65]. Notable examples of α-alloys include ASTM Grades 1–4 and Ti–Pd alloys (ASTM Grades 7 and 11). Near-α alloys, which consist predominantly of the α-phase with small amounts of β-stabilizers, offer a balance of strength and formability, making them suitable for a wide range of applications [66]. Alpha–beta (α–β) alloys feature a controlled mixture of α and β phases, providing an optimal combination of strength, ductility, and heat resistance. These properties make them widely applicable across diverse industries. Prominent examples include Ti-6Al-4V and Ti-6Al-6V-2Sn, both known for their excellent mechanical performance and broad availability [67, 68].

Beta (β) alloys are primarily composed of the β phase and are stabilized by elements such as vanadium and molybdenum. Compared to α–β alloys, they emphasize ductility over mechanical strength and are employed in specialized industrial applications [69, 70].

Notable β-alloys include Ti-13V-11Cr-3Al and Ti-11.5Mo-6Zr-4.5Sn. Beta-metastable (near-β) alloys consist predominantly of the β phase with limited α-stabilizers, emphasizing ductility over mechanical strength compared to α–β alloys. Moreover, Nitinol, although technically a nickel–titanium intermetallic, is often considered among titanium alloys due to its extensive use in biomedical applications, despite its high nickel content [71, 72]. However, as it is an intermetallic rather than a traditional alloy, it will not be extensively discussed in this article. Additionally, Table 2 presents examples of alloys with varying chemical compositions, highlighting both underutilized and highly sought-after alloys like Ti-6Al-4V, renowned for its unique properties and significant demand across numerous industries. Understanding the classification and characteristics of these alloys is essential for selecting the appropriate material for specific industrial needs.

Table 2. Classification of titanium-based alloys with examples.

Category	Examples
Alpha alloys	Commercially pure titanium—ASTM Grades 1, 2, 3, and 4 Ti/Pd alloys—ASTM Grades 7 and 11 Ti-2Cu
Near alpha alloys	Ti-8Al-1Mo-1V Ti-6Al-5Zr-0.5Mo-0.2Si-IMI 685 Ti-6Al-4Zr-3Sn-2Mo-0.08Si Ti-5.5Al-3Zr-3.5Sn-0.3Mo-1Nb-0.3Si-IMI 829
Alpha-Beta alloys	Ti-6Al-4V Ti-6Al-6V-2Sn Ti-4Al-4Mo-4Sn-0.5Si Ti-6Al-2Sn-4Zr-6Mo
Beta alloys	Ti-13V-11Cr-3Al, T-13V-11Cr-3Al Ti-11.5Mo-6Zr-4.5Sn
Metastable beta alloys	Ti-3Al-8V-6Cr-4Mo-4Zr-Beta C Ti-6V-6Mo-5.7Fe-2.7Al-TIMETAL 125 Ti-15V-3Cr-3Sn-3Al

Nickel is present in approximately 60% of stainless steels and serves as a crucial austenite stabilizer in Fe–Cr–Ni alloys. It reduces the ductile–brittle transition temperature, thereby enhancing toughness, ductility, and resistance to brittle fracture, particularly at low temperatures [73-75]. Nickel also improves the corrosion resistance of stainless steels, particularly in acidic environments, and enhances their formability and weldability. Nickel–chromium stainless steels were first developed in Germany in the 1940s and saw widespread use during World War II. However, restrictions on nickel availability during the Korean War prompted the development of low-nickel and nickel-free stainless-steel grades.

Stainless steels are designated according to the AISI system, which classifies steels based on their chemical composition and properties. Common grades include AISI 304, containing approximately 18–20% chromium and 8–10.5% nickel; AISI 316, which incorporates molybdenum for enhanced corrosion resistance; and AISI 430, a chromium-rich grade without nickel [76, 77]. Based on microstructure, stainless steels are broadly classified into austenitic, ferritic, martensitic, duplex, and precipitation-hardened stainless steels [34, 78].

Austenitic stainless steels constitute the largest family of stainless steels, accounting for approximately 65–70% of total global production. They possess a face-centered cubic (FCC) crystal structure, which remains stable from cryogenic temperatures up to the melting point. [79]. These steels are generally non-magnetic in the annealed condition; however, slight magnetism may develop after cold working. Austenitic stainless steels cannot be hardened by heat treatment and are instead strengthened through cold working [80]. Their microstructure is primarily stabilized by nickel and nitrogen, which imparts excellent corrosion resistance, superior formability, high weldability, and outstanding toughness, even at cryogenic temperatures. Common examples include grades 304 and 316. In contrast, ferritic stainless steels contain approximately 10.5–27% chromium and little or no nickel [81, 82]. Ferritic stainless steels possess a body-centered cubic (BCC) crystal structure and are inherently magnetic. They exhibit moderate corrosion resistance and superior resistance to stress corrosion cracking compared to austenitic stainless steels. However, they generally display lower toughness and reduced weldability, largely due to grain growth in the heat-affected zone during welding. [83, 84]. Typical ferritic stainless steel grades include 430 and 409. Martensitic stainless steels contain higher carbon contents, typically ranging from 0.1% to 1.2%, which enables heat treatment to achieve high strength and hardness. These steels are magnetic and generally exhibit lower corrosion resistance than austenitic stainless steels [77]. Owing to their ability to be hardened through heat treatment, martensitic stainless steels are commonly used in applications such as cutlery, turbine blades, and surgical instruments. Duplex stainless steels, in contrast, exhibit a mixed microstructure composed of approximately equal proportions of austenite and ferrite [85, 86]. This dual-phase microstructure integrates the advantageous characteristics of both austenite and ferrite, resulting in high strength, enhanced corrosion resistance, and excellent resistance to stress corrosion cracking. Despite these benefits, duplex stainless steels require strict control during welding and are generally unsuitable for prolonged exposure to very high temperatures [87, 88].

Duplex stainless steels are widely used in offshore structures, heat exchangers, and chemical processing equipment. Precipitation-hardened stainless steels attain high strength through the formation of fine precipitates within the microstructure during controlled heat treatment [89]. These steels provide higher strength levels than both austenitic and martensitic stainless steels while maintaining good corrosion resistance. As a result, they are commonly used in aerospace components and high-performance engineering applications.

The corrosion resistance of stainless steel arises from the formation of a passive chromium oxide film on the surface. This film is extremely thin, invisible, and self-healing in the presence of oxygen [90, 91]. When damaged, the passive layer can reform as long as oxygen is available; however, if oxygen is absent, localized corrosion or staining may occur. Stainless steel is also highly sustainable, with approximately 88% of stainless-steel products being recycled worldwide [36, 92]. Importantly, the recycling process does not degrade corrosion resistance, making stainless steel a preferred material in environmentally conscious engineering applications.

Cast Co–Cr alloys are produced through a casting process that involves melting the alloy, pouring the molten material into a mold of the desired geometry, and allowing it to cool and solidify to form the final component [93]. An example of a cast Co–Cr alloy with widespread applications in implants and medical devices is the F75 grade. This alloy is typically shaped using the investment casting process, also known as the “lost-wax” process, which begins with a wax pattern that is later replaced by the molten metal to produce the final component [94, 95].

The wax pattern is first coated with a ceramic material, and then the wax is melted out to create a ceramic mold. During manufacturing, the Co–Cr F75 alloy is melted at 1350°C–1450°C and poured into the ceramic mold to form the desired shape for implants, such as partial denture frameworks, femoral stems of artificial hips, and other medical devices [96, 97].

After solidification, the ceramic mold is broken to remove the solidified metal for further processing into the final device. Depending on the casting conditions, three different microstructural features have been observed that could adversely affect the corrosion and mechanical properties of the alloy: [98] an alpha phase Cobalt-rich matrix along with metal carbides (Co23C6, Cr23C6, and Mo23C6) at the grain boundaries and inter dendritic regions [99]. Relatively, the alpha (α) and carbide phases in cast Co–Cr alloys should ideally be present in proportions of 85% and 15%, respectively. However, due to the non-equilibrium conditions that occur during cooling, the resulting microstructure often contains interdendritic regions enriched in Cr, Mo, C, and carbides [100] whereas, the dendrites lack Cr and are enriched with Co. This is electrochemically unfavorable since the Cr lacking regions become anodic when compared to the remainder of the microstructure. This could have an adverse impact on the corrosion resistance of the alloy; (2) the solidification process in casting not only forms dendrites but also large size (4 mm) grains, which decreases the yield and tensile strength of the alloy [101].

Several studies have shown that grain size has a significant influence on the corrosion behavior of Co–Cr alloys. Therefore, the grain size should be carefully optimized to achieve a balance between mechanical strength and corrosion resistance. Additionally, casting defects are common in these alloys and may act as stress concentrators, potentially leading to fatigue fractures of implants under in vivo conditions.

Forged Co–Cr alloys are initially cast and then subjected to thermomechanical processing, which involves applying intense heat and pressure through methods such as pressing, hammering, or rolling to shape the alloy into the desired form. Examples of forged Co–Cr alloys include F799 and F961 grades [102]. The F799 alloy is processed by hot forging at 800°C following casting. The primary difference between forged F799 and cast F75 alloys lies in the thermomechanical processing performed after casting. The forging process involves a series of steps at varying temperatures to achieve the desired final shape. While high temperatures facilitate alloy deformation, they may also reduce the strength of the material if not carefully controlled [103]. Therefore, high temperatures are applied only during the early stages of forging to facilitate deformation, while lower temperatures are used in the final stages to maximize cold working and strengthen the alloy. As a result of this cold working, a solid-state phase transformation occurs in parts of the microstructure, changing from a face-centered cubic (FCC) to a hexagonal close-packed (HCP) crystal structure [103].

Cold working is widely applied to enhance the mechanical strength of the alloy. During this process, a solid-state phase transformation occurs in parts of the microstructure, where the crystal structure changes from face-centered cubic (FCC) to hexagonal close-packed (HCP) [104]. Consequently, forged alloys exhibit superior fatigue resistance, yield strength, and tensile strength due to their distinctive microstructure. The coexistence of two different crystal structures impedes dislocation movement, thereby significantly enhancing the mechanical strength of the alloy compared with cast counterparts. Forged cobalt chromium (CoCr) alloys are currently among the most widely utilized alloy systems for medical devices implanted at load-bearing sites, particularly in artificial joint replacements. Examples of prosthetic systems manufactured from forged CoCr alloys include the Metasul® Metal-on-Metal articulation (Zimmer Holdings), the Accolade C Femoral Component (Stryker Corp.), the Echo™ Hip System (Biomet), and the AcuMatch® L-Series cemented stems (Exactech) [103].

3. Effects of Cold Rolling and Deformation Processing

Cold rolling and other thermomechanical deformation processes significantly enhance the mechanical properties of titanium, stainless steel, and cobalt-chromium alloys through work hardening, grain refinement, and dislocation strengthening [46]. In titanium alloys, particularly α and α+β types such as Ti-6Al-4V, cold rolling increases yield strength and ultimate tensile strength by up to 30–50% while maintaining acceptable ductility [53]. The process introduces a high density of dislocations and refines the grain structure, leading to improved fatigue resistance and reduced crack propagation rates critical for aerospace and load-bearing biomedical implants. Studies have shown that controlled cold deformation followed by annealing can produce a balanced microstructure that minimizes stress-shielding effects in orthopaedic applications [105, 106].

In stainless steels (especially austenitic grades 304 and 316L), cold rolling is the primary strengthening mechanism since these alloys cannot be hardened by heat treatment. Reductions of 30–50% in thickness can raise the yield strength from approximately 200 MPa to over 600 MPa through strain-induced martensite formation and dislocation entanglement [107, 108]. However, excessive cold working may reduce corrosion resistance by disrupting the passive film, necessitating a subsequent annealing step to restore ductility and passivity [109, 110].

Cobalt-chromium alloys also benefit from cold working, particularly in forged grades (e.g., F799). Hot forging followed by cold deformation transforms the face-centered cubic (FCC) structure partially into a hexagonal close-packed (HCP) structure, resulting in superior fatigue strength and wear resistance compared to cast counterparts [99, 111]. This dual-phase microstructure impedes dislocation motion, enhancing performance in articulating joint replacements.

Cold rolling and deformation processing remain powerful tools for tailoring the strength-fatigue balance of these alloys. When combined with proper annealing or surface modification, they enable the production of high-performance components with improved durability, making them indispensable for demanding aerospace and biomedical applications [112].

4. Various Applications of Titanium Based Alloys

Titanium-based alloys have garnered significant attention and application in the major field of aerospace industry due to their exceptional properties, where their lightweight yet strong characteristics are highly valued, making them a preferred choice for various critical components. From structural components to jet engine parts and spacecraft components, these alloys contribute to enhanced performance, efficiency, and reliability in aerospace applications [27]. Titanium alloys, especially Ti-6Al-4V, are widely used in aerospace structural components due to their high strength-to-weight ratio and excellent corrosion resistance. These properties make them suitable for airframe structures, landing gear, and other critical load-bearing aircraft parts [113]. Titanium-based alloys are essential in jet engine components. Their high-temperature resistance and durability in harsh environments make them suitable for turbine blades, discs, and casings, improving engine efficiency and reliability [114]. Titanium alloys are widely used for aerospace fasteners because of their high strength, lightweight nature, and strong corrosion resistance. They help secure critical components while reducing overall weight, improving fuel efficiency, and maintaining structural integrity. Titanium-based alloys are vital in spacecraft and satellite construction due to their lightweight and durable properties. They are used in structural parts, thermal shields, and satellite frames, ensuring reliability in the harsh environment of space [10]. Titanium-based alloys are essential in the aerospace industry due to their unique properties. They enhance structural strength, engine performance, fastening systems, and space technology, supporting continuous advancements in aerospace engineering [27].

Table 3. *Application of selected titanium-based alloys in the aerospace industry.*

Material	Application	
Commercially pure titanium	Airframe structure	Floors
Ti-6Al-4V		Windows frames
Ti-10V-2Fe-3Al; Ti-6-6-2		Landing Gear
Ti-3Al-2.5V		Hydraulic Tubing
Ti-15V-3Cr-3Sn-3Al		Springs
Ti-6Al-4V; Ti-6-2-4-2S	Gas Turbine Engines	Compressor Disc
		Compressor Blades
		Fan disc and blades
Ti-35V-15Cr		Compressor Stators
TIMETAL21S		Nozzle Assembly

Titanium alloys are often used instead of aluminium when operating temperatures exceed aluminum's limits. They are commonly applied in components such as nacelles, auxiliary power units, and wing anti-icing systems. For example, landing gear beams in aircraft like the Boeing 747 and Boeing 757 show how titanium helps overcome space and strength limitations, despite being more expensive than aluminum [8, 115].

Titanium's strong corrosion resistance often eliminates the need for painting, except when it contacts aluminum or low-alloy steel, which may cause galvanic corrosion. In highly corrosive areas, such as floor supports beneath kitchens and lavatories, titanium provides improved structural durability. Common titanium alloys used in airframe structures—such as floors, window frames, landing gear, and springs include commercially pure titanium, Ti-6Al-4V, Ti-10V-2Fe-3Al, Ti-6-6-2, and Ti-15V-3Cr-3Sn-3Al [16, 19]. Alloys such as Ti-6Al-4V, Ti-6-2-4-2S, Ti-35V-15Cr, and TIMETAL21S are widely used in gas turbine engine components, including compressor discs, compressor blades, fan discs and blades, compressor stators, and nozzle assemblies [116, 117]. Moreover, Table below provides further details on the application of titanium materials in aerospace, categorized by alloy type, reinforcing the versatility and importance of titanium in this industry

Compared to stainless steel and cobalt–chromium alloys, titanium's biocompatibility and corrosion resistance make it ideal for medical implants and devices. Titanium alloys are commonly used in orthopedic implants such as joint replacements, bone plates, and dental implants because they integrate well with tissue and endure the body's harsh physiological conditions [118]. The biomedical industry mainly uses commercially pure titanium Grade 2 and Ti-6Al-4V Grade 5 for over 95% of titanium-based devices. ELI (extra-low interstitial) alloys are also common, offering similar compositions but with much lower interstitial element content [118]. Reduced interstitial elements like oxygen, nitrogen, hydrogen, and boron improve titanium alloys' ductility and fracture toughness. These alloys are used in biomedical devices, including cardiovascular applications such as stents, pacemaker cases, and heart valve components, thanks to their biocompatibility and corrosion resistance in bodily fluids [119].

Titanium and its alloys are crucial in cardiovascular devices, improving patient outcomes by restoring blood flow, supporting cardiac function, and providing structural strength. They are used in coronary and peripheral vascular stents to open blocked arteries, helping prevent heart attacks and other complications.

Titanium alloys are widely used in cardiovascular devices due to their biocompatibility, corrosion resistance, and mechanical properties. They are employed in mechanical heart valves to replace damaged tissue, ensuring proper blood flow, and in pacemaker and ICD enclosures to protect electronics from bodily fluids and electromagnetic interference. Titanium is also used for electrode tips. For stents, titanium and other metals like stainless steel, platinum iridium, tantalum, and cobalt–chromium maintain vessel openness, often coated with titanium oxide or nitride to prevent restenosis. Heart valves also use anti-adherent coatings to reduce cellular build-up. Alloys such as Ti-6Al-4V, commercially pure titanium (Grade 2), and Nitinol are favored for their strength, corrosion resistance, biocompatibility, and unique features like shape memory and superelasticity [2, 118].

Table 4. *Medical applications of some Titanium based alloys.*

Material	**Application**
Commercially pure titanium, Ti-6Al-4V, Ti-6Al-7Nb, Ti-15Mo, Nitinol Application	Cardiovascular devices (heart connectors, valves, catheters, implantable defibrillators, ventricular assist devices)
Commercially pure titanium, Ti-6Al-4V, Ti-6Al-7Nb, Ti-15Mo, Ti-13Nb-13Zr, Nitinol Application	Orthopedic implants (hip and knee joints, meshes, bone substitute, fixation devices).
Commercially pure titanium (grades 1, 2, 3, and 4), Ti-6Al-4V, titanium, Ti, Nitinol Application	Dental implants (braces, bridges, fixation devices, abutments)
Commercially pure titanium, Ti-6Al-4V, Ti-6Al-7Nb Application	Trauma devices (screws, plates, nails, nodes).
Commercially pure titanium, Ti-6Al-4V, Ti-6Al-7Nb Application	Soft tissue implants (breast reconstruction meshes, hernia meshes, fixation devices).

Orthopaedic implants: Titanium and its alloys are key in musculoskeletal devices, including joint replacements and fixation components. Their strength and biocompatibility allow implants to integrate with bone, withstand physiological loads, and improve patient mobility, function, and quality of life [120, 121].

While cobalt–chromium alloys have been effective in orthopaedics, titanium offers key advantages: better osseointegration and a higher strength-to-weight ratio, resulting in lighter implants. Titanium is not used for articulating components due to wear and tribo-corrosion limits but is ideal for load-bearing parts like femoral stems and acetabular cups in hip replacements, providing stability and transferring mechanical loads to bone. It is also used in non-articulating implants such as ribcages, skull implants, spinal cages, and bone scaffolds where its durability and low wear ensure long-term reliability. Common orthopaedic titanium alloys include Ti-6Al-4V, Ti-6Al-7Nb, Ti-15Mo, Ti-13Nb-13Zr, and commercially pure titanium [118, 120, 121]. Each titanium alloy has properties tailored to specific orthopaedic applications, including load-bearing implants, spinal implants, bone screws, and fixation devices. Despite issues like ion release and stress shielding, titanium implants have shown exceptional longevity, with some lasting over 30 years. Dental prosthetics: Titanium's biocompatibility and corrosion resistance make it ideal for dental implants, crowns, bridges, and orthodontic appliances, improving patient comfort and outcomes. Dr. Per-Ingvar Brånemark's discovery of osseointegration the direct bonding of bone to titanium paved the way for its widespread use. Titanium posts, placed in the jawbone, integrate with bone to provide a stable base for prosthetic teeth [122, 123]. Titanium dental implants restore chewing and speech, prevent bone loss, and preserve facial structure. In orthodontics, titanium's strength-to-weight ratio and corrosion resistance make it ideal for braces, wires, and other devices, allowing controlled tooth movement. Its biocompatibility and corrosion resistance help implants withstand oral challenges like pH changes and bacteria, ensuring durability. Long-term studies show titanium dental devices have survival rates over 95% after 10 years [124, 125].

In dentistry, common titanium alloys include β-titanium, Ti-6Al-4V, commercially pure titanium, and Nitinol, used for wires, brackets, bone plates, and orthodontic arch wires. Surgical and trauma instruments: Titanium's strength, durability, and corrosion resistance make it ideal for forceps, retractors, and scalpels. Ti-6Al-4V and commercially pure titanium are most used, with the latter prized for its biocompatibility and stable oxide layer that enhances safety and longevity [126, 127]. Trauma devices, bone plates, screws, and intramedullary nails require materials that can withstand high mechanical stresses in the body. Titanium, cobalt–chromium, and stainless steel are commonly used, although titanium may be less resistant to cyclic fatigue than stainless steel. Despite this, titanium offers better biocompatibility and lower infection risk. Implant design must consider anatomical location since titanium's relative softness can produce cytotoxic particles through wear. In screws, shaft fractures occur more often than thread fractures due to bending stresses. Locking plates provide greater stability but may increase stress on bone and tissue. Common titanium alloys used in trauma devices include Ti-6Al-4V, Ti-6Al-7Nb, and commercially pure titanium [128, 129].

5. Comparative Analysis and Biocompatibility of Titanium, Stainless Steel, and Cobalt–chromium Alloys

Titanium, stainless steel, and cobalt–chromium alloys each possess distinct properties that make them suitable for specific engineering and biomedical applications. Titanium alloys, particularly Ti-6Al-4V, are widely recognized for their superior strength-to-weight ratio, being about 45% lighter than steel while maintaining high mechanical strength. They also exhibit exceptional corrosion resistance and a relatively low elastic modulus, closer to that of natural bone. These characteristics make titanium alloys highly suitable for aerospace structures, load-bearing orthopaedic implants, and cardiovascular devices where weight reduction, durability, and biological compatibility are essential.

Stainless steels, especially austenitic grades such as 304 and 316L, provide cost-effective corrosion resistance due to the formation of a stable chromium oxide passive layer. Their good formability and mechanical properties make them practical for general engineering applications and some biomedical devices. However, the presence of nickel in these alloys may lead to ion release, which can cause allergic reactions or hypersensitivity in certain patients during long-term implantation. Consequently, stainless steel is more commonly used for temporary implants, trauma fixation devices, and applications where long-term biological integration is less critical.

Cobalt–chromium alloys, on the other hand, are known for their exceptional hardness, wear resistance, and excellent tribological performance. These properties make them particularly suitable for high-wear biomedical components such as articulating surfaces in hip and knee joint replacements. Despite their advantages, cobalt–chromium alloys have a higher density and elastic modulus than bone, which may contribute to stress shielding and potential bone resorption over time. Additionally, the release of cobalt and chromium ions, although generally lower than nickel release from stainless steel, can still raise concerns regarding cytotoxicity or hypersensitivity in some cases.

Biocompatibility remains a key factor in the selection of metallic materials for biomedical implants. Among the three alloy families, titanium alloys demonstrate the highest level of biocompatibility. The naturally formed and stable titanium dioxide (TiO_2) passive layer provides excellent resistance to corrosion in physiological environments and minimizes the release of harmful ions. Moreover, the elastic modulus of titanium alloys is closer to that of cortical bone, which helps reduce stress-shielding effects and promotes osseointegration, the direct structural connection between bone and the implant surface. These advantages make titanium alloys the preferred materials for many orthopaedic and dental implants, including hip stems, spinal cages, bone plates, and dental abutments.

In contrast, stainless steels offer acceptable but comparatively lower biocompatibility. Although their chromium oxide layer provides corrosion protection, the nickel content present in conventional grades may cause inflammatory responses or allergic reactions in a portion of patients. While improvements such as low-carbon or nickel-free stainless steels have been introduced, these materials are still mainly used for temporary implants or cost-sensitive medical devices. Cobalt–chromium alloys provide good biocompatibility along with superior wear resistance, making them ideal for articulating joint surfaces. However, their high elastic modulus can create significant stiffness compared to bone, increasing the likelihood of stress shielding. To improve their biological performance, surface treatments such as plasma spraying or ion implantation are often applied to reduce ion release and enhance implant longevity. Overall, titanium alloys provide the best combination of lightweight performance, corrosion resistance, and biocompatibility, making them highly suitable for long-term implants and aerospace applications. Stainless steels offer economical versatility with adequate corrosion resistance but are more appropriate for temporary or less demanding biomedical uses. Cobalt–chromium alloys dominate in applications requiring exceptional wear resistance, particularly in joint-bearing components. Therefore, the selection among these alloy families ultimately depends on factors such as mechanical strength requirements, cost considerations, corrosion environment, wear resistance, and long-term biological compatibility.

6. Conclusion

Titanium, stainless steel, and cobalt-chromium-based alloys continue to be indispensable materials in both high-performance engineering and biomedical applications due to their excellent corrosion resistance, mechanical properties, and biocompatibility. This review has presented a comprehensive classification of these alloys based on chemical composition, microstructure, and thermomechanical processing. Titanium alloys were categorized into α, α+β, and β types; stainless steels into austenitic, ferritic, martensitic, duplex, and precipitation-hardened families; while cobalt-chromium alloys were differentiated into cast and forged variants.

The complementary strengths of these three alloy systems are evident across applications. Titanium alloys excel in aerospace structures and load-bearing biomedical implants owing to their superior strength-to-weight ratio, low density, and excellent osseointegration. Stainless steels offer cost-effective corrosion resistance and good fabricability, making them suitable for temporary implants and general engineering uses. Cobalt-chromium alloys remain the material of choice for articulating surfaces in joint replacements due to their outstanding wear resistance and tribological performance.

Despite these advantages, challenges such as stress shielding, ion release, high processing costs (especially for titanium), and fatigue performance under cyclic loading still limit their full potential. Advances in low-modulus β-titanium alloys, nickel-free stainless steels, surface modification techniques, and additive manufacturing are progressively addressing these limitations and expanding the application window of these materials.

In summary, the unique microstructure–property relationships and processing versatility of titanium, stainless steel, and cobalt-chromium alloys ensure their continued dominance in demanding sectors. Future research should focus on developing next-generation alloys with optimized biocompatibility, reduced elastic modulus, improved wear resistance, and sustainable manufacturing routes to meet the evolving requirements of aerospace, biomedical, and other advanced engineering fields.

Author Contributions

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Conflicts of Interest

The authors declare no conflicts of interest.

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