FUDMA Journal of Engineering and Technology
ISSN: 3092-9385
https://fjet.fudutsinma.edu.ng/index.php/fjet/
Volume 2, Issue 1, 2026, 389-394

Metal-Based Biomaterials for Clinical Implant Applications: Materials and Performance – A Review

Vincent B. ONIGBARA[1*], Sunday I. AGU[2], Muftau A. GBENLE[3]

[1*]Department of Welding and Fabrication Engineering Technology, Federal Polytechnic, Ilaro, Nigeria
[2,3]Department of Metallurgical Engineering Technology, Federal Polytechnic, Ilaro, Nigeria

[1*]vincent.onigbara@federalpolyilaro.edu.ng, [2]ikenna.agu@federalpolyilaro.edu.ng, [3]gbenle.muftau@federalpolyilaro.edu.ng

Abstract
Biomaterials are very essential to clinical implant applications because they make it possible to replace, repair, or enhance damaged tissues and organs. Among the various types of biomaterials available, metallic biomaterials are regularly adopted for medical implants because of their exceptional strength, robustness, and capacity to tolerate load-bearing circumstances. The key characteristics needed for biomaterials are covered in this review, including resistance to wear, durability under cyclic stress, protection against corrosion, and biocompatibility. Additionally, it highlights the properties and biomedical uses of widely used metallic biomaterials, including stainless steels, tantalum, nickel–titanium alloys, dental alloys, titanium and its alloys, zirconium–niobium alloys, and cobalt–chromium alloys. The review also lists the main drawbacks of metallic implants, such as wear debris generation, corrosion, metal ion release, toxicity issues, and stress shielding. In general, enhancing implant effectiveness and directing future advancements in biomedical materials require an awareness of the characteristics, uses, and difficulties of metallic biomaterials.

Keywords: *Clinical implants, biomaterials, metallic implants, biomedical engineering, medical implants.*

1.0 Introduction

The reliable utilization relating to materials designed for body part replacement became a reality towards the closing phase of the 19th century [1]. Parts of body systems in humans can be successfully replaced by multiple human-developed materials and systems [3]. These materials known as biomaterials are very unique in nature due to their compatibility with biological systems and also operate in close proximity to living tissues [4]. With a roughly 70-year history, biomaterials research encompasses aspects of tissue engineering, medicine, metallurgy, biology, physics, and chemistry [10]. In line with the European Society for Biomaterials definition, a biomaterial can be defined as any material that is capable of interacting with living systems in a bid to replace, treat, or improve bodily organ, tissue or system [4, 14].

Biomaterials fall under the category of engineering option that involves the synthesis and the advancement of materials that come into contact with body tissues and bodily fluids with the intention of treating, enhancing, or replacing anatomical elements of the human body [5]. Typical essential categories of materials and their transition from ordinary materials to designed biomaterials are titanium, polyurethanes, hydroxyapatite, silicones, bio glass, Teflon, polyethylene glycol, hydro-gels, to mention a few [9]. The body rarely reacts negatively to or rejects biomaterials [4]. Implants are devices derived from biomaterials for bone-related applications which are produced for a wide range of orthopaedic uses [2]. Implants can reside inside the human body, either for short or for a prolonged duration. A typical example is soft contact lenses which can be fixed for a short time while hip replacement implants can exist in humans for a lifetime [11].

The design, development and synthesis harmless, effective and potent biomaterials for human use involves the contribution of scientists across several disciplines like metallurgy, medical science, chemistry, physics, and biology [3].

2.0 Essential Biomaterial Features

A biomaterial should have the characteristics listed below.

i. Biocompatibility: This is a term used to describe a material which in a particular situation is capable of functioning with a host response [4]. This feature is a prominent factor to consider when selecting a biomaterial. The metallic implant is prone to environmental corrosion, which causes the implant to degenerate and the implant material to break down [6]. This will negatively impact the surrounding organs and tissues. It is important to ensure that the synthesized biomaterial is harmless for human use and does not contain adverse effects [8].

ii. Mechanical features: To enhance the durability of the implant and reduce the occurrence of revision surgery, it is crucial that the implant material possesses the desired mechanical features [3]. Low modulus

Received: 15/03/2026; Revised: 28/03/2026; Accepted: 02/04/2026; Published: 21/04/2026

and high strength are among the mechanical characteristics that prevent loosening. It is important that the elastic modulus of biomaterials lies within the limits of the human bone, typically between 4 and 30 GPa [3]. In this case, there will be less likelihood of stress shielding.

iii. Lengthy fatigue life: The material needs to have a lengthy fatigue life. For hip prosthesis, implant failure due to repeated loading has been reported [11].

iv. Strong resistance to corrosion: When a biomaterial prone to chemical degradation is surgically introduced into a person, it might release metallic ions into the body system and cause harmful effects [6]. Thus, it is important to choose an implant material that is not easily susceptible to corrosion. The implantation site is a corrosive media which is typically subjected to cyclic loading. As a result, metal implants are susceptible to corrosion during their services [8]. Fretting, pitting, and fatigue corrosion are common types in implant applications.

v. High wear resistance: The implant material should posses a high wear resistance, and its coefficient of friction should be typically low [8]. This is because a decreased wear resistance or an increased friction coefficient can make the implant become loose. Additionally, the wear residue may result in inflammation that damages the implant's supporting bone.

vi. Osseointegration is a term used to explain the structural and functional relationship between a living tissue and the outermost part of an implant that carries load [16, 17, 18]. A metallic-based implant achieves osseointegration when it remains fixed relative to the bone it is in contact with. According to Branemark's research, titanium implants may be permanently incorporated into bone [18]. It implies that the implant's layer of titanium oxide may bond with the biological bone tissue to the point where it would be impossible to remove them without breaking.

vii. Non-toxic: The biomaterial must not exhibit toxic effects so as to fulfill its function without negatively impacting body tissues and organs' biological systems. Therefore, the substance shouldn't be either cyto-toxic (damaging individual cells) or geno-toxic (altering the genome's DNA) [12].

viii. Economic aspect of the biomaterial: Cost is the final factor considered when selecting a metallic material for implants [3]. Based on their intended use, the prices of fabrication and machining operations can differ significantly, and some metals are significantly costlier than others as raw materials.

3.0 The Significance of Alloys or Metals as Biomaterials

Over the years, metals have played significant contributions to the development of science and technology [3]. This is stemming from the advances and ground-breaking researches in engineering materials in contemporary times. The biomaterial industry is significantly impacted financially by metallic implants [5]. Considering their superior electrical combined with their thermal conductivity and necessary mechanical qualities, metals serve as biomaterials [4].

Metals exhibit properties that render them feasible for load-bearing applications; however, proper processing of their strength and fracture resistance will enhance durability of their implant's performance in areas requiring load-bearing applications [10]. Since metals have varying mechanical features, some exhibit higher performance than others in particular circumstances.

Depending on how they are processed, metals with similar compositions can behave differently [3]. To ensure that implants work as intended while in use, it is crucial to comprehend the characteristics of the materials and the methods employed to obtain desirable attributes during the manufacture of metallic components [11]. Metallic biomaterials were preferred for these devices as they are still utilized in the development of surgical implants [4]. Metals perform the role of implants in several parts of the body of human being.

In actuality, a metal implant will withstand failure brought on under repeated stress application and will need a large load to deform [10]. Metals neither shatter easily nor break suddenly and don't harm patients. Due of their superior mechanical qualities and corrosion resistance, a number of metals are utilized as alternatives to hard body tissue replacement, and applications include joints (knee and hip), screws, dental implants, bone plates, spinal fixation devices, to mention a few [2]. Certain metallic alloys have greater involvement in device operations like vascular stents, cochlear implants, orthodontic arch and catheter guide wires, to mention a few [9]. In the meantime, the material purity and processing methods of metals determine their mechanical properties.

The human body can only handle very small quantities of the majority of metals used to produce alloys for implants [6]. The body holds minimal quantities of tungsten, iron, niobium, titanium, chromium, tantalum, nickel, cobalt, and molybdenum. At times, metallic elements that are in natural form are essential in small concentrations during the production of vitamins or red blood cells. For instance, cobalt aids the synthesis of vitamin B12 while iron aids the production of red blood cells.

4.0 Alloys or Metals Used as Biomaterials

The first metal ever known to perform the role of a biomaterial is vanadium [11]. It was used to fabricate screws and bone fracture plates. Other materials commonly used as biomaterials include the following:

4.1 Stainless Steels

The first hip implant was produced using stainless steel around 1960 [11]. This was accomplished through advances in metallurgy, coupled with improved surgical techniques. The foremost class of stainless steel selected for implant applications is the 18-8 stainless steel. This material is both stronger and able to resist corrosion better than vanadium steels [4]. As time progresses, grade 316 or 316L stainless steels became popularly used as biomaterials [4]. The inexpensive, ease of manufacture and machining are factors that favour stainless steels in non-permanent fracture fixation systems. Despite their design for corrosion resistant purpose, stainless steels are not the best alloys for corrosion resistance of medical implants [6]. Stainless steel is often only utilized for implants that are meant to remain in human's body for a short time (less than a year) because it will eventually corrode, particularly around joints and cracks.

Benefits and Drawbacks: While stainless steel materials offer certain benefits over other metals, like high strength, ductility, toughness, and ease of machining. They also present limitations, including corrosion issues and a greater elastic modulus compared to the human bone [3]. Besides, they possess less bonding ability than other metals.

Applications: Spinal devices, screws, heart valve, dental root implants, dental fixture for tooth support, fracture plates, joint replacements, hip nails, bone plates, shoulder prostheses, stents, to mention a few [2].

4.2 Ti and Its Alloys

Titanium's use as a biomaterial implant dated back since 1930 [11]. Titanium and stainless steel have comparable yield strengths. However, its elastic modulus is approximately half the elastic modulus of stainless steel, making it a better option for clinical implant use [3]. Titanium osseointegration and direct mineral apposition at the interface between bone and titanium result from this biomaterial's elevated surface energy and favourable body reaction following implantation [7]. Titanium shields itself against corrosion by forming titanium oxide (TiO_2) surface film [6].

Additionally, titanium along with its alloys are frequently praised for its mechanical qualities, which include their strength and low weight [9]. The two types of titanium utilized in implants are Ti-6Al-4V (ELI), which is also called extra low interstitial and (CP-Ti), commonly referred to as commercially pure titanium. These alloys of titanium are characterized by their inert nature and are also utilized as biomaterials [9]. These materials termed biologically inert biomaterials are free from the hazard of nickel hypersensitivity and other allergic reactions in their enclosed tissues, unlike some categories of stainless steels [13].

Titanium possesses unique physical properties that classify it as a biomaterial. These include excellent corrosion resistance, electrical conductivity, the ability to form low ion in aqueous solution, and the ability to achieve a stable thermodynamic condition at normal body pH levels [6].

4.2.1 Pure Ti

This material exhibits allotropy. Above 882°C, it exhibits a BCC (body-cantered cubic) structure and below this temperature, it possesses a hexagonal close packed structure (HCP) [3]. This material has a surface property that can form an inert and stable oxide layer; it is adjudged the best metallic material with biocompatibility features [4]. An amazing feature of titanium is its lightness. It has a density of 4.5 g/cm3. The concentration of titanium in CP-Ti is an essential factor in determining its fatigue, tensile and yield strengths. Typically, this is in a range of 98.9 to 99.6%.

4.2.2 Ti-6Al-4V alloy

It is also called Ti-6Al-4V ELI, in which it combines titanium with roughly 6% aluminium and 4% vanadium [9]. The ELI stands for "extra low interstitial," which indicates that the alloy contains relatively few impurities like iron and oxygen. The metal becomes less strong but more ductile with the ELI classification. Additionally, it strengthens the alloy's resistance to fatigue fracture and increases its fracture toughness. It is extensively utilized in the production of implants and its chemical needs. Titanium alloys rank among the most intriguing metal-based materials for biomedical use [9]. They have consistently been preferred for biological applications.

Through regulated composition and thermo-mechanical processing techniques, the alloys of titanium can be strengthened and their mechanical characteristics altered [3]. When exposed to oxygen, titanium burns easily and becomes extremely reactive at high temperatures. As a result, it must be treated at high temperatures in an inert atmosphere or through vacuum melting. Titanium quickly absorbs oxygen, and the dissolved oxygen causes the metal to become embrittled. Any forging or hot working activity involving this material should not exceed 925°C. Ti-6Al-4V alloy's approximate fatigue strength is 550 MPa, which is the same as Co-Cr alloy.

It is relevant to note that aluminium and vanadium are poisonous upon their release into the body. However, with the aid of the oxide layer of titanium on the alloy's surface, corrosion and toxicity are resisted by inhibiting the release of Aluminium and Vanadium ions into the human system [6].

Studies have shown that the titanium alloy (Ti-6Al-4V) has greater strength than pure titanium, although both materials possess good corrosion properties, biocompatible, effective bonding to bone tissue, and reduced elastic modulus [9]. However, the resistance to wear features of Co-Cr-Mo alloys and stainless steels is higher than both of them.

4.3 Cobalt-chromium alloys

The alloys of cobalt -chromium have the following composition: 58–70% cobalt, 26–30% chromium, and trace amounts of nickel, molybdenum, titanium, tungsten, iron, to mention a few [4]. These alloys are in two categories: Co-Cr-Mo and Co-Ni-Cr-Mo alloys. The former is cast while the latter is forged. Over the years, Co-Cr-Mo alloys have been broadly utilized in dentistry and in recent times, it has been utilized for the synthesis of artificial joints [9]. The forged alloys are able to withstand wear relative to the cast alloys; however, research has shown that they possess a higher friction coefficient than the cast alloys. In contemporary times, the stems of prostheses are manufactured from the forged Cobalt-Nickel-Chromium-Molybdenum alloy. This is highly applicable for knees and hips which accommodate highly loaded joints.

The stems of prostheses for the joints of the knee and hip are currently fabricated from the Cobalt-Nickel-Chromium-Molybdenum alloy. The overall performance of a metal implant within the body depends on factors like its external features and mechanical behaviour [4].

Benefits and Drawbacks: Benefits of Co-Cr alloys include long-term implantation in the human body, high strength, heavy load support, fracture and wear resistance, to mention a few [9]. However, these alloys are highly costly, and it is challenging to fabricate medical implants that meet precise specifications. In addition, these alloys have modulus that is higher than the human bone.

Typical applications: Applications include surgical instruments, joint and bone replacements for knees and hips, micro plates, dental restorations, orthopaedic prostheses, dental implants, sutures, bone plates for fracture fixation, dental root implants, heart valves, to mention a few [2].

4.4 Ni-Ti Alloys (Nitinol)

Ni-Ti has been explored medicinally since 1970s [9]. The remarkable qualities of titanium-nickel alloys enhance their usefulness in surgical applications. Ni-Ti is anticipated to offer new exceptional capabilities, great performance, and possess the capability for utilizing simple and modern procedures in specific surgical implants. As against traditional metal alloys, Ni-Ti is intriguing as a biomaterial due to its excellent damping features, shape memory effect, and elastic properties [12]. The alloy possesses Shape Memory Effect (SME), a feature that gives it the ability to revert to its original configuration after being heated and subsequent distortion. This unique feature reinforces the alloy with good elastic properties and corrosion resistance.

Benefits and drawbacks include low Young's modulus and allergy-causing Ni. Ni-Ti's high nickel concentration raises the possibility that nickel will corrode from the material and have negative effects. Before Ni-Ti alloys may be utilized for implant purposes safely, their biocompatibility must be taken into account [13].

Applications: they serve to produce bone plates, orthodontic wires, and stents. Besides, they are utilized for cardiovascular stents. Ni-Ti appears to be generating a lot of attention and fame within the commercial and medical sectors right now. Currently, orthopaedic, dental, and cardiovascular applications employ Nitinol. Self-locking and self-expanding and compressing implants that activate within the room temperature are made possible by it [12].

4.5 Zr-Nb Alloy

Zr-2.5Nb alloy was the first alloy developed for the nuclear industry [11]. Zirconium, one of its constituent elements is highly reactive. When the metal is exposed to an environment that is rich in oxygen, it forms Zirconium oxide (ZrO_2), which is an oxide layer that is heavy and cohesive [6]. This oxide provides a surface that is wear and corrosion resistant.

Applications: To make orthopaedic implant components in regions like hips and knees where compressive stress and wear resistance is required.

4.6 Dental Alloys

Since ancient times, dental implants were synthesized from metals and alloys [9]. According to research, evidences are found in pre-Common Era archaeological records from Egypt and China. The first dental implants were made in these nations using ivory and stone. In the sixteenth and seventeenth centuries, dental implants made of ivory and gold were utilized. Metals along with their alloys such as Ti-6AI-4V, titanium, Fe-Cr-Ni based alloys, Ti-based alloys, Co-Cr-Mo based alloy, cast Ti components, Ti-Cu, Ti-Co alloys, CP-Ti, Ti-Cu-Ni, to mention a few, have found application within the area of dentistry [9]. They are essentially useful in the field of dentistry for tooth fillings, synthesis of bridges and crowns, fabrication of dental implants, orthodontic wires and brackets [12].

Benefits and Drawbacks: Similar to orthopaedic uses, metal's strong inherent strength and fracture resistance are its main advantages for dental applications.

4.7 Tantalum

Evidence suggests that the electrochemical process of metal corrosion has unfavourable impacts [6]. Tantalum is a bio-inert metal, which has been successfully utilized in the field of medical science since metal corrosion adds to human body's rejection of metals. As a result of the creation of an impenetrable tantalum oxide (Ta_2O_5) coating that shields the metal surface and prevents it from harmful chemicals, such as acids and alkalis, tantalum has been widely believed to be biocompatible [6]. Tantalum can function as a biomaterial in two ways. These are either as nanoparticles or in porous form. In recent times, porous tantalum has found application in orthopaedics to address issues with implant loosening [15].

Due to its extreme porosity, porous tantalum has some remarkable mechanical qualities. It possesses a low modulus of elasticity which is likened to the human bone, improves load distribution and reduces the stress shielding phenomena. When it comes to biomaterials, its friction coefficient is one of the greatest, enabling adequate primary stability of implants. Tantalum was first employed to fabricate surgical sutures owing to its extreme strength and ductility [19]. Owing to its osteoconductive and potentially osteoinductive qualities, its application has shown excellent outcomes, particularly in challenging instances with significant bone defects.

Benefits and Drawbacks: Excellent corrosion resistance in situations involving charge transfer and elevated voltage potential.

Applications: Porous tantalum is utilized in fields including spine surgery, hip osteonecrosis surgery, and hip and knee replacement surgery. It is made out of pure tantalum placed on a carbon scaffold [15]. In the future, tantalum nanoparticles may find application in targeted delivery of medication for the purpose of treating conditions including cancer and degenerative disc disease [2]. Electrodes are also made from tantalum.

5.0 Limitations of Metal-Based Biometallic Materials

1. Toxic consequences result from the inclusion of certain elements like Cobalt, Chromium, and Nickel, both in Co-Cr alloys and stainless steel [13]. Dermatitis is caused by Ni poisoning.
2. Neuropathy, Alzheimer's disease, and osteomalacia had been associated with long-term exposure to vanadium ions in titanium alloys and aluminium [5].
3. It has also been stated that the presence of Co can cause cancer. According to recent reports, hazardous elements including Co, Ni and Cr are typically present in Co-Cr alloys and stainless steels. Furthermore, the 6Al-4V alloy contains cytotoxic components like vanadium and aluminium that, if released into the human body, could result in serious issues [6].
4. For the majority of constructed structures, mechanical failure is unacceptable. This is especially true for surgical implants, where failure may cause patient discomfort, maybe even death, or necessitate difficult and sometimes fatal revision surgery [11].
5. An inflammatory response brought on by wear fragments and a high coefficient of friction may cause implants to loosen as a result of osteolysis [8].
6. Implant failure results from stress shielding caused by an elevated elastic modulus [3].

6.0 Conclusion

Considering the exceptional mechanical strength, longevity, and capacity of metallic-based biomaterials to perform well in load-bearing implant applications, they are highly essential to biomedical engineering. Materials like titanium and its alloys, stainless steels, tantalum, zirconium–niobium alloys, cobalt–chromium alloys, and Ni–Ti alloys are often employed in orthopaedic, cardiovascular and dental implants because of their unique features like mechanical qualities and resistance to corrosion attack. Titanium-based materials are especially prized for their superior biocompatibility and osseointegration ability. Despite these benefits, metallic biomaterials still have a number of drawbacks that could affect the longevity and functionality of implants, such as corrosion, metal ion release, toxicity issues, wear debris production, and stress shielding. To create superior metallic biomaterials with increased biocompatibility, less toxicity, and greater mechanical compatibility with biological tissues which will ultimately result in safer and more robust medical implants, further research and technological developments are required.

References

[1] C. M. Agrawal, “Reconstructing the Human Body Using Biomaterials,” *JOM*, Jan. 1998, pp. 31–35.
[2] W. D. Callister Jr., *Materials Science and Engineering: An Introduction*, 6th ed. New York: John Wiley & Sons, 2003.
[3] R. M. Pilliar, “Metallic Biomaterials,” in *Biomedical Materials*, R. Narayan, Ed. Springer, 2009, pp. 41–79.
[4] Q. Chen and G. A. Thouas, “Metallic implant biomaterials,” *Mater. Sci. Eng. R Rep.*, vol. 87, pp. 1–57, 2015.

[5] R. Davis, "A comprehensive review on metallic implant biomaterials and manufacturing," *PMCID*, 2022.
[6] N. Eliaz, "Corrosion of metallic biomaterials: A review," *Materials*, vol. 12, no. 3, p. 407, 2019.
[7] H. Ghodrati, A. Goodarzi, M. Golrokhian, F. Fattahi, R. M. Anzabi, M. Mohammadikhah, and S. Mirhadi, "A narrative review of osseointegration and anti corrosion of titanium dental implants," *Bone Reports*, vol. 25, 2025.
[8] G. Manivasagam, D. Dhinasekaran, and A. Rajamanickam, "Biomedical implants: Corrosion and its prevention," *Open Biomed. Eng. J.*, pp. 40–60, 2015.
[9] E. Marin and A. Lanzutti, "Biomedical applications of titanium alloys: A comprehensive review," *Materials*, vol. 17, no. 1, 2023.
[10] J. Naveen, T. Khan, and S. H. Khahro, "Advancement in biomedical implant materials—A mini review," *Front. Bioeng. Biotechnol.*, vol. 12, 2024.
[11] R. L. P. Teixeira and P. C. D. Silva, "Advancing metallic biomaterials for biomedical implants: A comprehensive integrative review," *Rev. Gestão Soc. Ambient.*, vol. 18, no. 5, 2024.
[12] B. Sumrita and A. K. Ashok, "Biomaterial in Regenerative Medicine," *J. Postgrad. Med. Educ. Res.*, vol. 46, no. 2, pp. 81–89, 2012.
[13] A. Swalsky, S. S. Noumbissi, and T. G. Wiedemann, "Titanium implant corrosion and hypersensitivity reactions," *Int. J. Implant Dent.*, vol. 10, p. 58, 2024.
[14] R. L. P. Teixeira and P. C. D. Silva, "Advancing metallic biomaterials…," 2024.
[15] S. H. Weeden and R. H. Schmidt, "Tantalum porous metal implants," *J. Arthroplasty*, vol. 22, pp. 151–155, 2007.
[16] G. Zhu, G. Wang, and J. Li, "Advances in implant surface modifications," *Mater. Adv.*, vol. 2, pp. 6901–6927, 2021.
[17] C. Pandey, D. Rokaya, and B. P. Bhattarai, "Osseointegration of dental implants," *BioMed Res. Int.*, 2022.
[18] P. I. Brånemark, "Osseointegration and its experimental background," *J. Prosthet. Dent.*, vol. 50, no. 3, pp. 399–410, 1983.
[19] G. L. Burke, "The corrosion of metals in tissues," *Can. Med. Assoc. J.*, vol. 43, pp. 125–128, 1940.