

Review Article

Metallic Biomaterials in Biomedical Implants: A Review of Materials, Manufacturing Processes, and Emerging Trends

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Received 24 April 2025

Revised 15 August 2025

Accepted 15 August 2025

Abstract:

Biomedical implants are artificial human-made devices designed to replace damaged hard tissues in the human body caused by fractures, accidents, diseases, and the natural effects of aging. Metallic biomaterials (MBMs) are commonly used in biomedical implants because of their excellent mechanical strength, stiffness, and durability. Consequently, the global demand for metallic biomaterials is growing rapidly and steadily, driven by the aging population and a rise in the incidence of injuries and diseases. This review highlights the various types of biomaterials and the processing methods used to fabricate medical implants from metallic biomaterials. It also highlights applications of biomaterials and machining processes. To encourage further research in this area, this review concludes with a summary and suggestions for future research.

Keywords: *Metallic biomaterials, Biomedical implants, Conventional machining methods, Advanced machining methods*

1. Introduction

Nowadays, chronic diseases, aging populations, and higher rates of injuries and accidents worldwide are driving the demand for metallic materials [1-2]. Furthermore, the continuously growing global population, environmental pollution, extreme weather (i.e., heatwaves, droughts, floods, and wildfires), and food chain contaminants are also contributing to the rise in diseases, accidents, and various health issues. As a result, there is a heightened need for high-quality, durable medical tools, as well as various medical equipment, including diagnostic devices, treatment tools (such as surgical instruments and auxiliary equipment), and biomedical implants [3-5]. Surgical blades, knives, scissors, scalpels, needles, needle holders, drills, and suturing are some specialized surgical instruments used by healthcare professionals for various purposes, including removing bones, excising or eliminating abnormal structures, repairing diseased tissues or organs, clearing obstructions, repositioning bones or organs at standard position, transplanting tissues or organs, implanting mechanical or electronic devices, isolating and dissecting lesions [6-8]. Additionally, they are used in cosmetic surgeries to enhance physical appearance [9]. A biomedical implant is a synthetic device designed to replace or support a diseased or damaged natural organ or tissue, functioning without causing harm to other parts of the body. In other words, they restore damaged body parts' mobility and function [10]. Biomedical implants, devices, and tools are made from biomaterials, which possess unique qualities such as durability, biocompatibility, and compatibility with surrounding tissues. Biomaterials interact with biological systems and are widely used in medical and health sectors [4, 11].

These sectors used different types of biomaterials, such as metallic, non-metallic, and composites. Each biomaterial has unique properties and applications. Biomaterials differ from traditional materials due to their specific properties and are used in a wide range of medical and healthcare applications, including bioimplants, surgical tools, and medical instruments. Some typical applications of biomedical and dental implants made from biomaterials are bone plates, sutures, braces, wires, rods, and a variety of fastening devices. Stainless steel, titanium, magnesium, nickel-chromium

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(NiTi) alloy, and cobalt alloy are metallic biomaterials (MBMs). These MBMs are considered the ideal choice for medical implants and surgical tools to replace damaged biological structures and support and enhance the existing biological structure. Bone plates and fixtures are used to support the damaged existing structures, whereas artificial implants, such as knee joints, are used to replace damaged knees. Biomedical implants and surgical tools are often made from MBMs because of their superior qualities, including high strength, stiffness, fatigue resistance, corrosion resistance, biocompatibility, and long-lasting durability. These characteristics make them ideal for medical applications where reliability and performance are crucial [13-17].

MBMs are often used as replacements for damaged hard tissues and bones caused by fractures, accidents, disease, and the aging population. Additionally, their use for joint replacements has significantly increased in recent decades. As a result, these biomaterials play a crucial and transformative role in restoring the quality of life for millions of patients worldwide. Estimates suggest that degenerative and inflammatory diseases affect 90% of people over the age of 40 [4, 12, 18]. Both traditional and non-traditional methods are employed for machining or processing these materials to manufacture biomedical implants, dental implants, surgical tools, and other medical devices. But machining MBMs by traditional machining methods is a challenging task due to certain machining constraints such as tool wear, surface quality, machining accuracy, tool marks, cracks, burr, sharp edges, etc [4, 12, 19]. It encourages researchers, academicians, and industrial users to investigate advanced machining or non-contact machining techniques to manufacture biomedical parts and components with better quality and close geometrical accuracy and tolerances. Advanced machining techniques such as wire-assisted electrical discharge machining (wire-EDM) and additive manufacturing (AM) are used to manufacture dental and medical implants made of MBMs with improved precision and accuracy [12, 20-21]. This study aims to highlight the various types of MBMs, as well as machining and manufacturing techniques to make medical implants and surgical tools from these materials. The details of biomaterials, machining of biomaterials, as well as recent challenges, conclusions, and identified future research directions, are discussed in the following sections.

2. Biomaterials and their classification

Biomaterials are biologically derived materials made to engage with biological tissue and the surrounding environment. Biomaterials originate from metals, ceramics, plastics, glass, and even living cells and tissue [22]. Materials used for biomedical and dental applications are commonly known as biomaterials or biocompatible materials. Biomaterials are crucial in biomedical applications, including implants and drug delivery systems [23]. Their compatibility with biological systems is essential for successful integration into the human body [24]. The interaction of materials with biological tissues is critical, influencing healing and integration. Surface properties of materials, including cleanliness and energy, significantly affect biocompatibility and bioadhesion [25]. Biocompatibility is essential for ensuring the safety and efficacy of materials used in medical applications, including implants, drug delivery systems, and tissue engineering [26]. Factors influencing the biocompatibility of materials are (i) the chemical composition of materials significantly affects their interaction with biological tissues, influencing cytotoxicity and immune responses [27]; (ii) the surface quality of materials is essential for cellular adhesion and proliferation [27-28]; and (iii) degradation behavior material significantly impact biocompatibility of materials. Nanomaterials are increasingly utilized in drug delivery and tissue engineering, offering great potential due to their exceptional characteristics [29-30]. Despite their potential, concerns regarding cytotoxicity and standardization in testing remain significant hurdles [30-31]. Bioimplant failure occurs prematurely due to wear, corrosion, poor fatigue strength, an uneven bone elastic modulus and implants, and non-bonding between surrounding tissues. Therefore, biomaterials should have poses some necessary characteristics such as biocompatibility with tissues and bones to avoid adverse reactions, nontoxic, noncorrosive, excellent mechanical properties (i.e. stiffness, elastic modulus, and strength), improved wear resistance and increased strength to withstand the cyclic loading, excellent degradation resistance to avoid corrosion in metals as well as biological degradation in polymers, ability to mold in various shape and size, and reliable chemical stability [32-36]. These materials should be easily accessible at a low cost. The appropriate selection of biomaterials generally depends on the types of biomedical and dental applications (i.e., implants, artificial teeth, dental braces, fixtures, and screws) and material characteristics. Biomaterials can be categorized into four groups, as discussed below [33-40] and shown in Fig. 1.

[i] *Metallic biomaterials:*

Stainless steels (SS), titanium and its alloys (i.e., Ti/Mg), magnesium and its alloys, nickel-titanium (NiTi)-based shape memory alloys (SMAs), cobalt-chromium alloys, and Nobel metal alloys are the preferred metallic biomaterials

(MBMs). Stainless steel belongs to the ferrous category, whereas SMA, titanium, Co-Cr alloys, magnesium, and Mg alloys fall under non-ferrous materials. MBMs are commonly used in load-bearing implants, including wires, screws, plates, and artificial joints such as hip, knee, and shoulder replacements. Table 1 presents the key mechanical characteristics of MBMs, while Table 2 details their limitations and applications in biomedical and dental fields.

[ii] *Inorganic/non-metallic biomaterials:*

Non-metallic biomaterials such as ceramics are extensively utilized as restorative materials in dentistry [41]. Bulk metallic glasses (BMGs), various forms of carbon (pyrolytic, graphite, and vitreous), zirconium oxide, titanium oxide, aluminum oxide, and vitro-ceramic materials are examples of ceramic materials. BMGs are metallic materials characterized by an amorphous microstructure, offering remarkable properties, including extreme hardness, corrosion resistance, tensile strength, fracture toughness, great elastic strain limit, thermal conductivity, electrical conductivity, and high rupture strength. These properties make them suitable for applications in optics, aerospace, sports, and biomedical [42].

[iii] *Organic biomaterials:*

Polymers and polymer composites are extensively used as organic biomaterials. They are non-metallic materials and are widely applied in facial prostheses, tracheal tubes, bladder implants, lenses, tendons, and more. Synthetic rubber, polyethylene, polyamide, polyetheretherketone, polyethylene terephthalate, poly-methylmethacrylate, polystyrene, polytetrafluoroethylene, and polyurethane are biomaterials based on polymers.

[iv] *Composite biomaterials:*

Carbon-filled polytetrafluorethylene (carbon-PTFE/Carbon-Teflon) and alumina-filled polytetrafluorethylene (Alumina-PTFE/ Alumina-Teflon) are composite biomaterials. Fiber-reinforced polymer (FRP) and glass fiber-reinforced composite are widely used for threaded implants. These biomaterials are widely used in dentistry as a restorative material, for bone repair, and joint replacement.

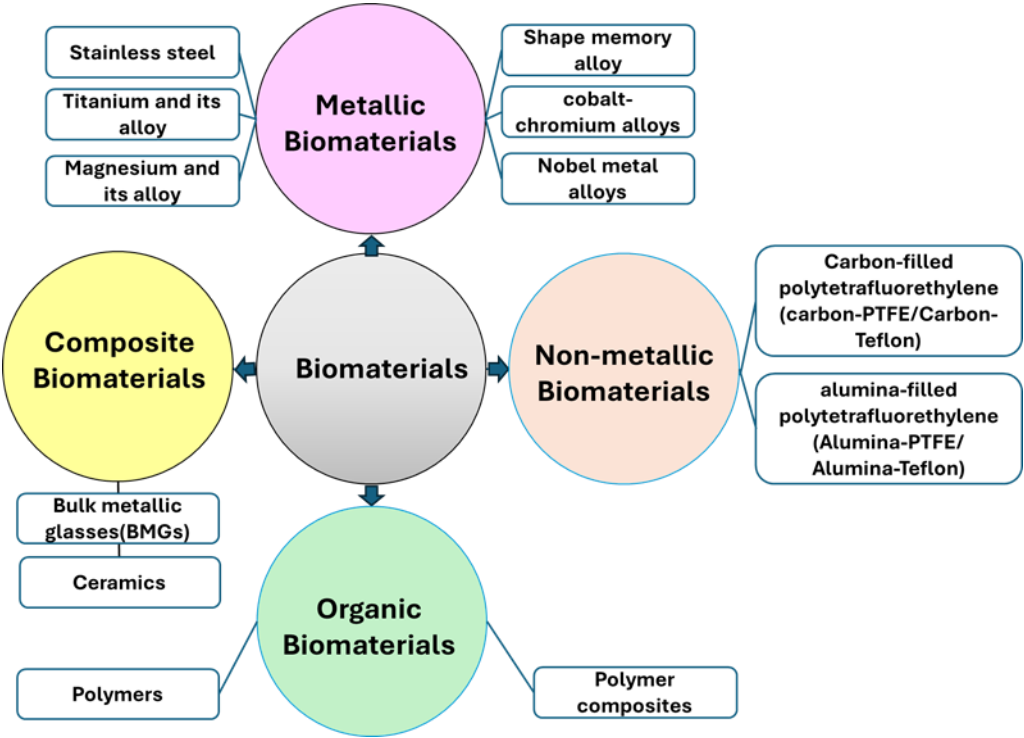


Fig. 1. Various biomaterials used in the medical and health sectors.

Table 1: Key mechanical characteristics of metallic biomaterials (MBMs) [4, 29, 34, 36].

Mechanical Properties	Metallic biomaterials (MBMs)				
	Stainless steel	Titanium and its alloys	NiTi-based Shape memory alloys (SMA)	Co-Cr alloys	Mg-based alloy
Yield strength (MPa)	220-600	380-951	195–690 (AP) 70–140 (MP)	242-655	148-200
Ultimate tensile strength (MPa)	500-1167	460-1120	895	795-1080	240-385
Hardness (HV)	130-367	1800	8	240-298	55-65
Elongation (%)	26-70	15-26	242-346	10-50	3-15
MPa: Megapascal, HV: Vickers hardness; AP: Austenite Phase; and MP: Martensite Phase					

Table 2: Biomaterials: characteristics and their biomedical and dental applications [4, 12, 33, 38, 39, 45, 55-58].

Serial Number	Biomaterials	Characteristics	Limitations	Biomedical applications
<i>Metallic biomaterials</i>				
01	Stainless steel	Excellent wear and corrosion resistance, adequate biocompatibility, and low cost	Stress and shielding effect	Orthopedic implants and fixtures such as screws, pins, and bone plates
03	Titanium and its alloys	Excellent biocompatibility, superior strength, high strength-to-weight ratio, reduced stiffness, and lower elastic modulus	High cost, poor machinability, and reduced fatigue strength under certain conditions	Biomedical implants: orthopedic implants [59], dental implants, fasteners, joint replacement [60], spherical prostheses, pacemaker casing, and spinal implants
04	Nitinol (NiTi) or SMAs	Biocompatible	High cost, dimensional instability, lower mechanical strength, and stiffness	Osteosynthetic plates, bone plates, stents, and micro-actuators
05	Co-Cr-based alloys	Excellent resistance to wear	Machinability, higher density, and dimensional variation under stress	Dentistry implants, sutures, hips, knees, and heart valves
06	Magnesium alloys	Excellent damping capacity, dimensional stability, machinability, biocompatibility, low density, and non-toxicity	Lower mechanical strength and modulus	Bone repair and vascular stents
<i>Other Biomaterials</i>				
07	Ceramics and BMG	Wettability, low friction, high wear resistance, and biocompatibility	Brittle, poor fatigue strength, and load-bearing capacity	Hip and knee implants
08	Polymers and their composites	Good biocompatibility, better corrosion resistance, better mechanical and fatigue properties	Lower strength and higher deformation	Hip and knee implants
09	Composites	Low modulus and high strength	Lack of consistency and homogeneity	Threaded implants
10	Bulk metallic glass (BMG)	High tensile strength, good resistance to wear and corrosion, good toughness, high elasticity, and low internal friction	Brittle, Processing complexity, and higher cost	Biomedical implants

2.1 Metallic biomaterials (MBMs)

The development of MBMs is crucial for the advancement of medical implants and devices. Overcoming the challenges of corrosion, biocompatibility, mechanical performance, and cost will lead to more effective, durable, and patient-friendly materials for various biomedical applications. Damaged tissues, bones, and structural parts can be replaced by artificial implants made from MBMs. Biocompatibility, durability, and tissue compatibility are some common characteristics of biomaterials. Apart from this, MBMs have some unique characteristics such as the ability to bear heavy loads; be non-toxic and integrate well with surrounding tissues without causing adverse impacts; degradation resistance from surrounding fluids, thus ensuring longer durability of metallic implants; customization, i.e., ability to be formed into intricate shape and size such as plates, screws, and prosthetic components, and available at a lower cost compared to other biomaterials. Stainless Steel, titanium and titanium alloys, cobalt-chromium alloys, magnesium alloys, nitinol (NiTi alloys) SMAs, and Nobel metal alloys are popular metallic materials used in the medical and health sectors. These materials are used in numerous medical applications, such as orthopedics, dentistry, and cardiovascular devices [43]. These materials are perfect for medical and dental implants, screws, braces, plates, artificial joints, and surgical tools due to their exceptional tensile strength, fatigue strength, and fracture toughness. Stainless steel is strong, cost-effective, and popularly employed in orthopedic implants, including bone plates and fasteners. However, it is prone to corrosion over time. Titanium and its alloys are highly biocompatible, with an excellent strength-to-weight ratio, making them popular choices for joint replacements, dental implants, and orthopedic implants. Cobalt-based alloys, particularly Co-Cr alloys, offer superior corrosion stability compared to stainless steel [43-44]. Co-Cr alloys are preferred for joint replacement implants due to their better strength and excellent wear and corrosion resistance [45, 46]. Co-Ni-Cr-Mo alloy, typically shaped through hot forging, is commonly employed in the fabrication of load-bearing stems for knee and hip prostheses [47]. Magnesium alloys have attained considerable attention as potential materials for biomedical implants due to their exceptional characteristics. However, their tendency to corrode in human body fluids limits their widespread use [48-49]. But they are promising materials for orthopedic applications. Moreover, the elastic modulus of these materials is close to that of natural bone, which helps limit stress shielding. Mg-based fracture fixation materials encounter challenges due to their rapid degradation in biological fluids, which results in a loss of mechanical integrity before the bone fracture has fully healed [50]. Therefore, additional research is needed to improve the corrosion resistance, mechanical properties, and bioactivity of these materials, making them suitable for orthopedic implants [51]. Kumar et al. [2020] highlight the past attempt made to machine magnesium alloys in dry conditions to determine the effect of machining variables on surface integrity and corrosion behaviour. Nitinol, or shape-memory alloys (SMAs), are known for their shape-memory and super-elastic properties [52]. It is commonly used to make stents, orthodontic wires, and surgical tools. Noble materials are widely preferred in restorative dentistry due to their high durability, stability, and excellent resistance to degradation [53-54]. Dental fillings, crowns, bridges, partial dentures, root canals, and dental implants are the most common types of dental restoration. Amalgam (a mixture of metals), composite resin (a tooth-colour material), porcelain, and gold are some commonly used dental restorative materials [43].

2.2 Adverse impact of biomaterials

Despite their benefits in medical implants, biomaterials have specific drawbacks that can affect their performance and biocompatibility.

- Metallic biomaterials: Strong and durable, but may corrode, releasing ions that cause inflammation or allergic reactions in surrounding tissues.
- Biodegradable polymers: Useful for temporary implants; however, their degradation by-products—often acidic, causing inflammation or interfering with normal tissue regeneration.
- Ceramics: Biocompatible and wear-resistant, but brittle and prone to sudden fracture under mechanical stress or impact.
- Composites: Offer tailored properties but risk delamination and uneven degradation, affecting structural integrity and biocompatibility.

2.3 Biomedical applications of metallic biomaterials

Biomaterials are natural or synthetic materials used in biomedical applications. Bioimplants are man-made structures commonly used as replacements for internally damaged body parts. The materials used for bioimplants must be biocompatible [55]. Human tissues and structures have a finite lifespan, but they can also suffer from several harmful

conditions like cancer, infection, and fractures that cause discomfort, deformity, or loss of function. Thus, one of the main uses of biomaterials is the replacement of unhealthy or damaged human structures or tissues with appropriate synthetic materials. Some typical applications of biomaterials are artificial hip joints, knee joints, sutures (threads for stitches used in surgery), bone plates, screws, cardiac pacemakers, intraocular lenses, etc. [33-38]. Figure 2 shows some typical biomaterials in medical and dental applications. The primary domains in which biomaterials are employed include (i) Orthopedic applications, such as prosthetics for joint replacement affected by conditions like arthritis; (ii) cardiovascular uses, including prosthetic arteries, heart valves, and **stents**; (iii) applications in ophthalmology, including contact lenses and synthetic (polymer) intraocular lenses; (iv) dentistry uses, including dental caps, prosthetic teeth, cavity fillings, and metallic braces; (v) wound healing such as sutures and graft; and (vi) drug distribution systems that enable regulated and focused drugs distribution.

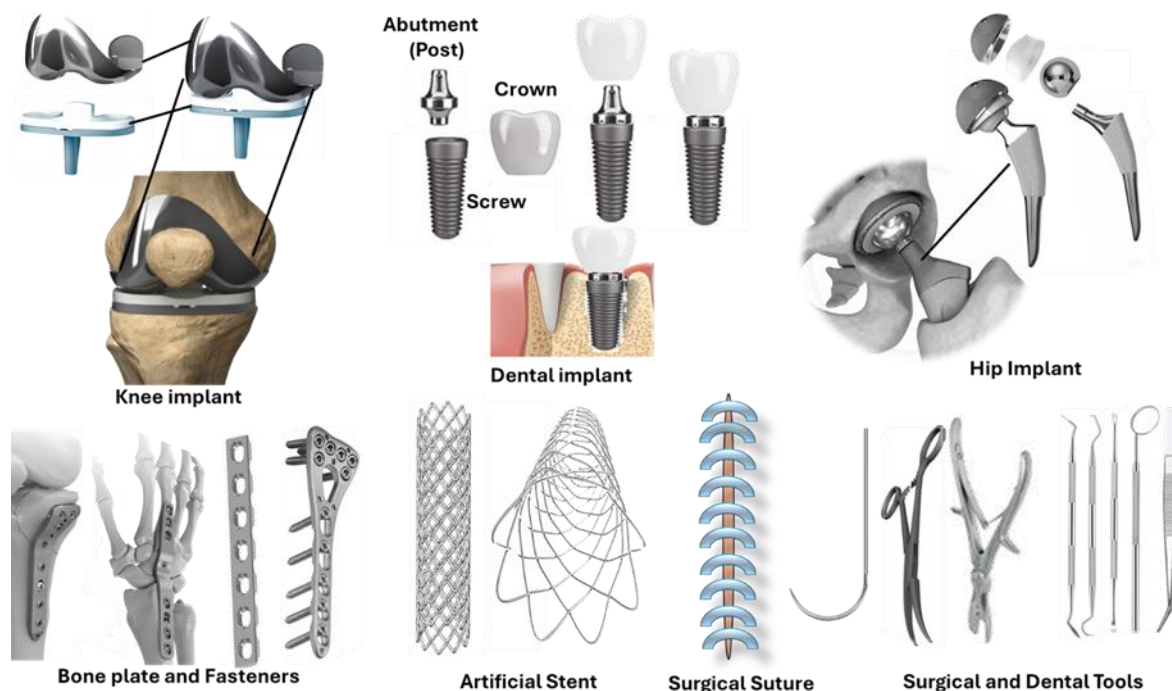


Fig. 2. Some applications of metallic biomaterials in biomedical implants and surgical tools.

3. Machining/Processing methods of biomaterials

The processing methods of biomedical parts and components are influenced by the type and nature of the biomaterials. Table 3 provides an overview of different processing methods suitable for fabricating a range of biomedical and dental components, including bio-implants, stents, dental braces, artificial teeth, fixtures, and screws, using various biomaterials. The methods for processing biomaterials to fabricate these biomedical and dental components can be classified into two groups, namely (i) machining processes and (ii) forming processes. Machining can be categorized as (i) conventional or contact-based machining methods, (ii) micro-machining methods, (iii) advanced or non-contact machining methods [4, 12, 61], and (iv) hybrid machining and finishing processes. Turning, milling, drilling, tapping, sawing, and grinding are traditional subtractive machining methods. Whereas, forming processes can be categorized as (formative processes, and (ii) deformative processes. Casting, powder metallurgy (PM), and injection molding are formative processes, whereas forging and extrusion are deformative processes. Micro-versions of these machining processes are used for machining small-scale parts and components. Traditional machining methods, such as casting, milling, drilling, grinding, forging, compression molding, etc., are commonly used for machining biomaterials but may limit the complexity of designs, surface finish, material restrictions, precision, and applications [23, 62-63]. Turning, milling, grinding, and their micro-scale counterparts are widely employed contact-type traditional machining methods used to manufacture biomedical and dental implants as substitutes for damaged inside body parts or structures [64]. These are subtractive-type machining processes in which the desired shape and size can be achieved by removing excess materials from work materials using single-point and multi-point cutting tools. Furthermore,

post-machining and post-treatment processes are necessary to produce the desired surface quality of manufactured bioimplants. These processes are quick and effective for machining MBMs. Milling is a subtractive process that cuts excess material from the workpiece using rotary multipoint cutters. It is employed for machining MBMs such as magnesium and titanium [45, 64-66]. Ball milling and abrasive water jet milling are also utilized to machine titanium and its alloys for biomedical applications [59-60, 67]. Milling is frequently employed in the production of artificial limbs and hip joint components. [60]. Casting, powder metallurgy, and injection molding are forming methods in which bio-parts and bio-structures can be fabricated by deposition of molten biomaterials in the desired mold in a single step. Machining and finishing processes are often employed after these forming methods to attain the required geometric accuracy and surface quality of formed parts. In casting, molten metal is poured into a mold to form a desired shape in a single step at a relatively low cost. Ti-alloys, Co-Cr alloys, stainless steel, and ceramics are biomaterials generally used in casting for making orthopedic joint implants and dental implants. In powder metallurgy (PM), metallic powders are compacted and sintered to form porous structures to enhance biomaterial integration with bone tissue. Ti-alloys, Co-Cr alloys, and stainless steel are commonly used in PM. Molding methods, such as injection and compression molding, are commonly used to shape MBMs, namely titanium alloys and magnesium alloys, under heat and pressure. These methods are employed for manufacturing biodegradable implants. Forging and extrusion are deformation methods that produce bioimplants such as hip joints by permanently shaping biomaterials through the application of compressive force.

The abovementioned traditional methods of machining or processing have several inherent limitations. These include the need for post-machining and finishing processes, their unsuitability for parts with complex geometries, special tooling requirements, excessive tool wear, rapid wear of forging dies, tool marks on machined surfaces, formation of burrs, inadequate edge definition, dimensional errors, poor surface finish, thermal and mechanical stresses, along with the presence of porosity and blowholes in casting and powder metallurgy processes [12, 68-70]. The challenges associated with traditional machining have compelled and motivated researchers and academicians to explore alternative methods for manufacturing MBMs. These new approaches include advanced machining processes, electrospinning, additive manufacturing, hybrid machining processes, hybrid additive manufacturing techniques, and abrasive finishing processes [71]. These processes allow greater control over material properties and geometries, enhancing biocompatibility [23, 69-70]. Laser beam machining (LBM), Electron beam machining (EBM), ion beam machining (IBM), electrical discharge machining (EDM), wire-assisted electrical discharge machining (wire-EDM), abrasive water jet machining (AWJM), and ultrasonic machining (USM) are advanced machining processes (AMPs) [12]. AMPs are becoming crucial for biomaterials, bioinspired materials, and biological materials to attain the desired surface characteristics. [4, 12, 71]. These processes are widely employed to machine these materials, manufacturing parts with intricate and complex structures that possess superior properties essential to their functionality [72]. LBM, IBM, EBM, USM, AWJM, spark-erosion-based machining such as EDM, wire-EDM, its small-scale variants, and hybrid machining are suitable for machining and drilling all kinds of biomaterials as listed in Table 1. However, EDM and wire-EDM are only suitable for electrically conductive materials. Therefore, the machining of polymers is not possible with spark-erosion-based machining methods. AWJM is associated with stray cutting, nozzle wear, noise, and the problem of handling abrasives. USM is best suited for machining brittle materials such as ceramics and is widely used for drilling and various cutting processes, such as slots and grooves. However, this method has a lower removal rate. Excessive tool wear, poor geometrical accuracy, and not suitable for soft materials. EBM is suitable for machining biomaterials with a thickness of less than 10 mm and operates under vacuum conditions only. IBM is widely used for milling, shaping, drilling, polishing, and cleaning biomaterials under vacuum conditions, but the capital cost is high. LBM is suitable for non-reflective materials. Laser cutting and engraving of thin ceramic is possible using a CO₂ laser [2, 9]. Nowadays, EDM and wire-EDM are widely used for machining titanium and shape memory alloys in biomedical and dental manufacturing industries [41, 71-75]. These processes are used for surface modification of MBMs [58]. EDM requires different fabricated tools for machining different biomedical parts and components. However, in wire-EDM, a thin wire is used for various types of cutting and turning operations of electrically conductive biomaterials to fabricate biomedical parts and fixtures [76-77].

Additive manufacturing (AM), also referred to as ‘rapid prototyping’ or ‘3D printing’, is an intelligent manufacturing process that is increasingly used for processing MBMs [78-79]. AM is a computer numerical and digital control-based (i.e., computer-aided manufacturing) process that involves the layer-by-layer deposition of a variety of metallic and non-metallic materials to create complex structures based on 3D model data [80-81]. While both AM and casting are material deposition processes, they differ significantly. In casting, the material is deposited in a single step to form a 3D object, whereas in AM, the object is built up gradually in multiple steps through the sequential deposition (i.e., layer upon layer) of molten materials according to the part program [82-83]. AM can be categorized into seven

distinct methods, namely (i) binder jetting, (ii) directed energy deposition, (iii) material extrusion, (iv) material jetting, (v) powder bed fusion, (vi) sheet lamination, and (vii) vat photo-polymerization [84]. AM-based processes are widely used in modern manufacturing industries such as medical, automotive, aerospace, and consumer goods [83, 85-86]. AM enables precise control over the internal structure of porous materials, facilitating the creation of specialized scaffolds for tissue engineering and regenerative medicine [87]. AM can produce customized implants and prosthetics with complex structures for orthopedic and dental applications, allowing for personalized patient treatment [88]. It has been reported from past work that AMPs are widely employed for making bioimplants made from Ti-, Mg-, and Fe-based biomaterials [89].

Hybrid machining processes are a combination of two different nature of machining methods (i.e., a combination of traditional and advanced machining), such as ultrasonic-assisted turning (UAT), electrical discharge grinding (EDG), wire electrical discharge grinding (WEDG), wire electrochemical discharge machining (WECDM), electrochemical discharge grinding (ECDG), and electrochemical grinding [90-94]. Hybrid additive manufacturing (HAM) integrates traditional machining with additive manufacturing to improve performance and functionality. Electron beam melting (EBM), AM (EBM-AMP), laser metal deposition (LMD), and RP (LMD-AMP) are some applications of hybrid additive manufacturing [95-96]. Metal-hybrid AM (MH-AM) combines traditional subtractive techniques, such as milling, turning, and grinding, with AM, enabling the production of highly complex, customized, and optimized metal parts with enhanced mechanical properties [80, 97]. Table 4 and 5 illustrate traditional machining methods and advanced machining methods and their suitability for biomaterials and biomedical applications, respectively. The development of advanced machining techniques and hybrid machining methods is crucial to support conventional methods, especially given the complex nature of biomaterials that require precision and structural integrity. Miniaturizing biomedical components poses challenges in precision and surface quality, particularly with mechanical methods like micro-milling, which face issues such as tool wear and heat generation. Advances in tool materials, coatings, and cooling techniques, along with hybrid machining approaches, help address these limitations. Further research into micro-scale machining will be essential for improving process stability, material removal rates, and tool longevity, advancing the manufacture of high-performance biomedical parts and components.

Table 3: Machining/processing methods to fabricate a variety of biomedical and dental implants from biomaterials [12, 97].

12, 27].

Machining/ Processing type	Nature of the machining	Machining methods	Machining processes
Conventional machining methods (Contact type)	Subtractive (material removal)	Chip formation	Turning, milling, drilling, tapping, and grinding
Forming processes	Formative (material addition)	Deposition	Casting, Powder metallurgy (PM), and Injection molding [34]
	Deformation	Shape formation	Forging and Extrusion
Advanced machining processes (non-contact type)	Melting and vaporization	Thermoelectric vaporization	Laser machining, EBM, and IBM
	Thermoelectric erosion	Controlled spark erosion	EDM, wire-EDM, and their variants
	Mechanical erosion	Abrasion	AWJM and USM
	Additive or accretion	Layer-by-layer deposition	Additive manufacturing (AM)
Hybrid machining processes	A combination of advanced and traditional machining methods		WECDM and ECDG
Post-machining processes (Finishing process)			
Conventional processes	Mechanical erosion	Abrasion	Hand polishing, mechanical polishing (i.e., lapping, honing, buffing, and superfinishing)
Advanced processes	Mechanical erosion	Abrasion	Abrasive flow finishing

Table 4: Traditional machining methods, suitable biomaterials, limitations, and biomedical applications [12, 42, 98-104].

Serial Number	Manufacturing Processes	Suitable biomaterials	Biomedical applications
Subtractive Processes (metal removal)			
01	Milling	Mg-alloy [98], Ti [65, 67, 74]	Artificial limb, hip implant [60]
02	Turning	SS, Ti, Ti-alloys, zirconia ceramics, Co-Cr alloys, NiTi SMAs, and Mg-alloys	Hip and Knee Implants such as femoral head stems, acetabular cups, dental implants, rods, screws, plates, needles, and scalpels,
03	Drilling and tapping	SS, Ti, Ti-alloys, cobalt-chromium alloys, zirconia, Co-Cr alloys, NiTi SMAs, and Mg-alloys	Bone screws, plates, dental implants, such as drilling jawbone, cranial implants, such as drilling into the skull
04	Grinding [99]	SS, Ti, Ti-alloys, Co-Cr alloys, and NiTi SMAs	Orthopedic implants, surgical instruments, stents, and catheters
Formative Processes (Metal Deposition)			
05	Casting [100]	SS, Ti, Ti-alloys, Co-Cr alloys, NiTi SMAs, zirconia, and Mg-Alloys	Bioimplants, prostheses, and surgical instruments
06	Powder metallurgy [101-102]	SS, Ti, Ti-alloys, Co-Cr alloys, NiTi SMAs, and zirconia	Orthopedic implants, surgical tools, dental implants, biodegradable implants, stents, and guidewires
07	Injection molding [103-104]	SS, Ti-alloys, Mg-alloys	Surgical tools, implants, and medical devices
Deformative Processes (plastic deformation)			
08	Forging [100]	SS, Ti, Ti-alloys, Co-Cr alloys, NiTi SMAs, and zirconia,	Orthopedic implants, surgical tools, dental implants, prosthetic joints, rods, and brackets
09	Extrusion	SS, Ti, Ti-alloys, Co-Cr alloys, NiTi SMAs, zirconia, and Mg-Alloys	Fixation devices, dental implants, bridges, crowns, medical wires, stents, surgical tools, and biodegradable implants

3.1 Key advantages of machining and fabrication processes for metallic biomaterials

The advantages of specific machining and processing methods for fabricating parts and components from biomaterials are discussed below.

3.1.1 Conventional machining methods

This includes methods such as milling, turning, drilling, and grinding, which offer several advantages in machining biomaterials—such as high precision and tight tolerances required for joint replacements and fixation devices, improved work hardening and fatigue resistance, clinical validation and regulatory approval, and cost-effective scalability for mass production.

3.1.2 Formative processes (material deposition processes)

This includes methods such as casting, powder metallurgy (PM), and injection molding, which offer several advantages for fabricating biomaterials. These include high material utilization through near-net-shape fabrication, uniform microstructure with fine, homogeneous grains for improved mechanical properties, suitability for mass production of small, complex parts (e.g., orthodontic brackets, surgical tools), alloy flexibility for creating custom compositions, and lower processing temperatures that reduce energy consumption.

3.1.3 Deformation processes (e.g., Forging and extrusion)

These methods provide numerous benefits, including improved mechanical properties, enhanced structural integrity, better surface finish, reduced material waste, and superior fatigue resistance.

3.1.4 Advantages of additive manufacturing (AM)

Techniques such as selective laser melting, electron beam melting, and direct metal laser sintering offer several benefits for biomaterial fabrication. These include customization for patient-specific implants (e.g., dental crowns, cranial plates), the ability to manufacture components with complex geometries, reduced material waste, rapid prototyping for faster design iterations, and the elimination of tooling requirements.

Table 5: Advanced machining methods, suitable biomaterials, and biomedical applications [12, 59, 105-106].

Serial Number	Manufacturing Processes	Suitable biomaterials	Biomedical applications
01	Abrasive water jet machining (AWJM)	Zr-based bulk metallic glass, Titanium, and its alloys, stainless steels, NiTi-based SMA	Orthopedic implants [59], dental prosthetics, surgical tools, cutting soft tissues, and cleaning and deburring of bio parts
02	Ultrasonic machining (USM)	Ti, Ti-alloys, Zirconia ceramics Natural teeth	Orthopedic joints, dental crowns, bone plates, and surgical instruments
03	Ion beam machining (IBM)	Biocompatible polymers, Ti, Ti-alloys, Co-based alloys, and SS	Surface Cleaning and Sterilization, customized implants, and surgical tools.
04	Electron beam machining (EBM)	Biocompatible polymers Dental composites	Orthopedic implants, dental prosthetics, and surgical instruments
05	Laser beam machining (LBM),	SS, MG-alloys, Ti, Ti-alloys, Biocompatible polymers, NiTi SMAs, Zirconia ceramics, and Bioactive glasses	Components for biomedical implants, surgical instruments, and microfluidic devices
06	Spark-erosion based machining	Co-based alloys, Ti, Ti-alloys, NiTi SMAs, Mg-alloys, Zr-based BMG, Ceramic-composite	Surgical instruments: forceps, scissors, and needle holders; Orthopedic implants: bone plates, screws, and hip joint components
07	Electrospinning	Polymer, Polymer composites	Scaffolds, artificial tissue, wound healing, and drug delivery carriers
08	Additive manufacturing process	Ti, T-alloys, NiTi SMAs, and SS	Orthopedic: hip and knee joints, Cranio-maxillofacial: skull and facial reconstruction, and dental applications, prosthetic limbs, braces, drug delivery systems, and Bioprinting of complex tissues
09	Abrasive Machining Process [106]	SS, Ti-alloys, and ceramics	Knee joint, hip joint, elbow joint, heart valve, and a dental crown

3.2 Limitations of machining and processing methods

Common limitations of various machining and processing methods used in biomedical applications, especially for implants, include the following:

- Conventional machining (milling, turning, drilling, grinding) methods can cause thermal and mechanical damage (e.g., microcracks, residual stresses) on biomaterial surfaces, potentially affecting fatigue strength and biocompatibility.
- Additive manufacturing allows for patient-specific implants and complex geometries, but issues remain with porosity control, repeatability, and mechanical integrity.
- Powder metallurgy parts may have inherent porosity that can weaken mechanical properties or allow bacterial infiltration.
- Challenges associated with injection molding include thermal degradation of some biomaterials and mold design limitations for complex medical parts.
- Hybrid machining has a high energy input may alter surface chemistry or cause unwanted toxicity or surface contamination

4. Challenges in advanced and hybrid methods for fabricating metallic biomaterial parts

The existing literature highlights the growing interest of researchers over the past few decades in exploring advanced machining, hybrid machining, additive manufacturing, and hybrid additive manufacturing of metallic biomedical materials to overcome the challenges of traditional machining processes. These manufacturing processes have drawn the interest of researchers due to their ability to produce customized implants with complex geometries while enhancing precision, material integrity, and surface quality. These advanced and hybrid manufacturing processes have various benefits over traditional machining methods, including enhanced precision and accuracy, reduced material wastage, the ability to produce complex geometries, smaller heat-affected zones, and enhanced biocompatibility, mechanical properties, and corrosion resistance of MBMs. In addition to the advantages listed above, advanced and hybrid manufacturing processes face several challenges. Key recent challenges in the manufacturing of metallic biomedical implants using these processes include [107-119]:

- Attaining optimal biocompatibility while maintaining mechanical strength, durability, and functionality.
- Adverse environmental impact of manufacturing processes for MBMs.
- Need to minimize degradation rates and improve the mechanical properties of biodegradable metallic materials such as Mg-alloys.
- Challenges of recycling critical materials, such as titanium, cobalt, and rare-earth elements.
- A necessity for post-processing (e.g., machining, polishing, heat treatment, and coating) to improve surface finish, mechanical properties, and biocompatibility.
- Fatigue failure and material degradation of metallic biomedical implants.
- Manufacturing customized implants or patient-specific implants to ensure a perfect fit.
- Selection of a suitable material and manufacturing process for biomedical implants.
- Specific limitations of MBMs, such as titanium, offer excellent biocompatibility but lower wear resistance than cobalt-chromium alloys, while stainless steel is strong but prone to corrosion over time.

5. Conclusions and future research directions

This review focuses on the biomaterials commonly used for biomedical implants, surgical tools, and medical devices, as well as the machining methods employed for these materials based on previous research on biomaterials and the appropriate machining processes for MBMs. Previous research concludes that (i) titanium and its alloys, NiTi-based SMAs, Co-alloys, Mg-alloys, zirconium-based BMS, ceramic composites, and stainless steel are frequently used MBMs in medical and dental implants; (ii) titanium and stainless steel are commonly used MBMs for bio-implants and medical fixtures due to their exceptional strength, corrosion resistance, and biocompatibility, and (iii) advanced machining methods are superior alternatives to traditional techniques for processing MBMs. EDM and wire-EDM are widely utilized to machine electrically conductive biomaterials with higher precision and accuracy. Due to the distinctive properties of MBMs, advanced and hybrid machining techniques have been increasingly investigated to address the limitations of traditional machining methods. These manufacturing methods offer enhanced precision and accuracy while also increasing productivity. Additionally, micro-machining methods are particularly valuable for manufacturing small-scale biomedical components and implants, enabling the production of intricate and customized parts required for specialized medical devices and surgical tools.

Future research directions

MBMs and their machining methods are crucial for medical implant development. Both material selection and fabrication impact biocompatibility, with fabrication processes influencing surface features such as surface finish and porosity to enhance biological response. Research should focus on new biomaterials with improved biocompatibility, mechanical properties, and degradation control. Advancing MBMs also requires exploring hybrid and advanced manufacturing processes for more efficient fabrication. Based on the findings of this study, the following future research directions are proposed:

- Evaluation of sustainability and productivity of advanced manufacturing through life cycle analysis
- Investigations on sustainable machining of MBMs.
- Exploration of the alternative manufacturing of MBMs.
- Development of 3D-printable materials using novel AM processes

- Integration of soft computing methods like Artificial Intelligence (AI) and Machine Learning (ML) for manufacturing biomedical parts.
- Optimization of machining parameters to enhance productivity and accuracy
- Investigations on micro-machining methods for the fabrication of small-scale, high-precision biomedical parts
- Sustainability, life cycle, and energy consumption for machining MBMs.
- Machining complex features from MBMs by advanced machining methods
- Evaluation of advanced machining sustainability and productivity through life cycle analysis
- Exploration of additive manufacturing for the development of biomedical materials and implants.
- Development of 3D printable materials processed using a novel AM process.
- Implantation of soft computing methods such as artificial intelligence (AI) and machine learning (ML) for manufacturing biomedical parts and the development of biomedical materials.
- Innovations in biofabrication—such as bioprinting and organ-on-a-chip systems—are shaping the future of biomaterials.
- Investigations on hybrid processes combining traditional and advanced techniques to enhance manufacturing efficiency and material performance.
- Investigations on micromachining methods for the fabrication of small-scale, high-precision biomedical parts and components.

Author contributions: Sujeet Kumar Chaubey: Conceptualization, methodology, organizing, writing-original draft, supervision, writing-review, and editing. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Competing interests: The authors declare no conflict of interest.

Nomenclature

<i>MBMs</i>	Metallic biomaterials
<i>BMGs</i>	Bulk metallic glasses
<i>SS</i>	Stainless steel
<i>NiTi</i>	Nickel titanium
<i>SMA</i> s	Shape memory alloys
<i>C_o-C_r</i>	Cobalt-chromium
<i>M_g</i>	Magnesium
<i>AMP</i> s	Advanced machining processes
<i>AM</i>	Additive manufacturing
<i>HMP</i> s	Hybrid machining processes
<i>RP</i>	Rapid Prototyping

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