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Review Paper

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Strategies to enhance Biocompatibility via additive manufacturing for medical applications: A state-of-the-art review

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ABSTRACT

In this review article, various cutting-edge strategies are addressed that aim to enhance the mechanical and functional properties of Biocompatibility metal, which are manufactured using additive manufacturing techniques, in particular for biomedical applications such as implants and prostheses. Additive manufacturing has several advantages, including time saving and cost reduction, especially in small product manufacturing processes and prototypes, freedom of design for complex shapes that are difficult to achieve by traditional methods, the advantage of reducing waste and material waste, the possibility of customizing products to order, enhancing sustainability and reducing environmental impact, and others. It can be said that most of the previous studies focused either on the biological properties of biometallics that were manufactured using addition techniques or improving mechanical properties, while comprehensive strategies that integrate the two aspects together have not been reviewed, and this article shows how to achieve synergistic improvements between the two performances. Any modern integrative revision combines various strategies (alloying, microscopic, surface, computational).

1. Introduction

The integration of additive manufacturing technology with the concept of prosthetic engineering and the basics of biological adaptation to the human body is one of the leading issues that have effectively contributed to enabling people who have lost limbs, as a result of accidents or diseases caused by amputation, to restore their daily motor functions and restore balance and physical structure. Over the past two decades, the research topic has witnessed significant qualitative leaps that have gone beyond the traditional boundaries of advanced biotechnology, including the design of innovative neuro-robotic control interfaces, sensory sensation restoration, the development of advanced biomechanics systems, as well as the application of advanced surgical techniques in the field of prosthetics, from both physiological and neurological perspectives [1]. Also, a thorough study of the functional performance and structural characteristics of implants produced with additional technologies, and comparing them with their traditional counterparts, showed a noticeable superiority in terms of performance and characteristics, reflecting the fundamental role of modern technologies in improving the quality and efficiency of prosthetics and their reliability [2, 3], controlling the deterioration of medical implants and implants, whether temporary or permanent, is crucial and necessary to reduce the risk of expected inflammation and avoid subsequent economic burdens, necessitating the adoption and selection of biocompatible biomaterials that guarantee functional stability and clinical safety [4]. Implant materials usually require a set of vital biological properties that affect in one way or another the growth of tissues and cells surrounding the implant materials, which affects the surface engineering and some techniques of modifying surfaces biologically for materials if they are inert, so improving the wear resistance and hardness of implant materials is an essential and important factor to ensure the best performance of functional and mechanical properties [5]. The aim of this review article is to provide a comprehensive overview of the common additive manufacturing technology used in the production of Biometals, especially those used in medical applications such as prosthetics or orthopedic implants, as well as analysis of the mechanical and biological properties of metals such as corrosion resistance, biocompatibility, hardness and strength, a review of the necessary strategies to improve the properties and functional performance, which include chemical and physical modifications and some of the surface treatments, and a comparison between the materials used and the methods used to determine efficiency and performance in biological applications. The article focused on a set of points that reveal the gap in the current studies, including the weaknesses of metals manufactured with modern technologies. Although additive manufacturing technologies provide unique possibilities (complex geometric shapes), metals produced by these methods suffer from: residual stresses, internal porosity, heterogeneous microstructure, and surface roughness. She also highlighted the absence of Comprehensive Integrative strategies. Most of the previous research has focused on improving one aspect (for example, improving corrosion resistance or reducing surface roughness, etc.), while Pepper points to the urgent need for comprehensive and integrated strategies that combine improvements in mechanical properties (such as strength and durability) and biological properties (such as biocompatibility and bone fusion) at the same time.

2. Methodology

The selection of literature for this article was based on several fundamental points, focusing on reliable databases and criteria for accurate study of biometallics manufactured with additional technologies during the period (2021-2025) and excluding non-metallic materials or studies not related to the medical field.

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Nomenclature

AM	Additive manufacturing	*WAAM*	Wire arc additive manufacturing
DED	Directed energy deposition	*CSAM*	Cold spray additive
LPBF	Laser powder bed fusion		

3. Biocompatible minerals in medical applications

Biocompatible metals (biocompatible implants) can be defined as programmed and developed medical materials and devices that replace amputated or damaged parts (parts with a biological structure), and the contemporary medical revolution in the field of biomaterials has increased the use of implants in medical applications such as prosthetics, Dental Implants, complete bone replacement, etc [6,7]. With the huge medical revolution and the continuous progress in the field of Biotechnology, the demand for innovative implant materials of high quality has become vital and increasingly vital to improve the experiences of technicians, specialists, and patients in general. Although conventional implants are still effective and non - biodegradable, the cost and requirements of surgical intervention in the traditional aspect have become necessary to remove or replace them in advanced ways and with great clinical challenges, therefore, biodegradable metals and their development has gained increasing importance due to its importance in its promotion as implants or its entry into manufacturing processes in prosthetic medical applications [8]. Bio-minerals are intended to interact with body tissues, which may be natural or artificial, depending on the design in which they are placed inside the body, taking into account not causing any side effects, they are classified according to their chemical, biological and physical properties and the correct choice of biomaterial in order to ensure the stability of the functional structure, durability and biocompatibility of medical devices, prostheses or dental implants, etc. [9]. The first metal that was used as implants in the human body was vanadium, which was used as plates and screws in surgical operations in bone fractures. Most of the metals used as implants, such as titanium, nickel, molopodium, and stainless steel, which can be compatible with the body as small parts, that is, if they are in large sizes, they can be exposed to corrosion and bio-failure, thus leading to tissue damage, we can say that the beginning of the use of bio-metals in medical applications in the XIX century, i.e. the beginning of the industrial revolution in ferrous and non-ferrous metals. Recently, mineral biomaterials and their uses in the restoration of solid tissues and organs have been extensively presented [10]. Perhaps the most prominent metals that are used in prosthetic medical applications are alloys based on titanium, cobalt-chromium, magnesium, in addition to stainless steel [11].

3.1 Overview of commonly used biometallics

3.1.1 Titanium and its alloys (Ti, Ti-6Al-4V)

Titanium and its alloys, one of the most common biocompatible metals, alloy (Ti-6Al-4V) has rapidly developed into one of the most important high-end materials among a variety of biomaterials that are used in industrial applications such as aerospace, biomedical, and energy, this is attributed to various reasons, perhaps the most prominent of which is its excellent corrosion resistance and specific strength, as well as low density, coupled with good toughness at a high temperature level, as well as the property of thermal softening at high temperatures. Nguyen, et al have shown that products manufactured by additive manufacturing exceed the speed of completion by conventional methods by about 25%, in addition, parts manufactured by additive manufacturing technology have a lower fatigue life than conventionally manufactured due to the presence of Greater residual tensile stress than traditional methods, as well as surface roughness, in addition to porosity [12]. Zhang et al. used the laser-assisted polishing method to enhance the integrity of the surface while comparing it with conventional methods, noting a decrease in surface roughness by (0,364 um) and an increase in the hardness of the surface structure from 324,4 hv to 464,8 hv with a noticeable enhancement in the thickness of the hardening layer and residual stresses [13]. For biomedical applications, the article by Nguyen et al. (2022) is the most relevant, directly linking additive manufacturing technologies and the behavior of Ti-6Al-4V in biogenic uses. In contrast, Zhang et al's article presents. (2025) is an important technical contribution to the improvement of surface properties, it can be considered complementary to the improvement of post-manufacturing performance, but it is less focused on direct vital aspects.

3.1.2 Cobalt-chromium (Co-Cr) alloys

Due to the unique physical and mechanical properties of (Co-Cr) alloys, this alloy has a wide range of uses in medical applications, where it can be used in the manufacture of Dental Implants, heart, orthopedic surgery, blood vessels and others. Mani et al. highlighted the failure of chromium-cobalt(Co-Cr) alloys in metal surface applications in hip surgery and its complete replacement and recommended the accuracy of the choice of material or biometal in special surgical operations [14]. Smith et al. reviewed mechanical experiments on samples processed by conventional methods and additive manufacturing (DED) methods, and the results of the latter showed a complex microstructure in addition to cellular, balanced, and vertical grains inside the melt pools, as well as higher hardness in addition to some properties [15]. Hassan Safi et al. conducted a study that dealt with the fusion of cobalt–chromium (Co–Cr) alloys with titanium and tungsten, with the aim of improving protection for head and neck tissues. The results showed that this alloy mixture enhances the absorption and dispersion of ionizing Rays used in radiation therapy, limiting the possible risks to body tissues [16]. If we make a comparison of the articles above, we will find that the article is (Smith et al, 2025) is capable of producing fine structures with high homogeneity and high density, which leads to a significant improvement in tensile strength and hardness as well as wear durability. Thus, the use of DED in the manufacture of metal implants can increase their functional efficiency in medical applications, by enhancing mechanical performance and reducing the likelihood of structural failure in complex biological environments.

3.1.3 Stainless steel (316L)

Due to the high elasticity, strength, resistance to high temperatures, as well as excellent corrosion resistance, the alloy of stainless steel 316L has gained an advantage for use in additive manufacturing [17,18]. The alloy of stainless steel 316L can be different in terms of its exact composition if the manufacturing method of that alloy (additive manufacturing and conventional manufacturing) is compared due to the hardening rates that are carried out during processing and thermal cycles during its printing [19,20]. Barionuevo et al. conducted an experiment using samples of 316L stainless steel with additive manufacturing (L-PBF), and the results of the experiment were that high porosity allows to reduce corrosion (the effect of nails on frictional properties) [21].Erdogan et al. They made modifications to the surface of the stainless steel alloy 316L by electrochemically treating the surface of the alloy using nanomembranes to enhance bone cell adhesion and somewhat reduce bacterial adhesion to increase its bioeffectiveness [22]. In terms of improving biomechanical and functional properties, the article by Erdogan (2023) is the most extensive and relevant to actual medical applications, since it is not limited to only physical properties, but goes beyond them to enhance the biological performance necessary for metal implants.

3.1.4 Zinc-magnesium (Alloy biodegradable metals)

Recently, biodegradable metals such as magnesium, zinc, and iron have been of great interest and attraction in the field of Biomedicine [23–25]. Through self-corrosion, these metals are biodegradable and gradually decompose in vivo, which reduces possible complications when performing tissue surgery on the body. Although magnesium alloys are known for their excellent biocompatibility, their decomposition speed is high [26]. Tesar et al. proved that wires made of magnesium with a small amount of zinc (0.4-1%) and coated with a polymer material strengthen the mechanical properties and improve bioendurance to be used in the support, binding, and fixation of bones inside the body [27]. Bukalov et al. demonstrate a new approach represented by the use of powder metallurgy made by batches to improve the mechanical resistance of the alloy used in medical implants and bone implants [28]. Article Tesař et al. (2024) are the best in terms of improving biomechanical and biofunctional properties together, because they offer a comprehensive biological assessment with obvious improvements in durability and biodegradability, promoting the application of these materials in biodegradable implants. An integrative approach should be adopted that combines improving the purity of the alloy, adjusting the microstructure, and modifying the surface by effective means, with comprehensive bioassays, with the aim of developing biodegradable metal implants with an optimal combination of strength, safety, and biocompatibility.

3.2 Ideal requirements for biominerals

3.2.1 Biocompatibility

Biocompatibility: it is a measure of the compatibility of materials and tools with body tissues according to a certain biological system. Perhaps the most prominent feature that should be characterized by the ideal biomaterial in medical applications is (inertness). There are many recent studies to expand the concept of biocompatibility [29]. The selection of biomaterials used in medical implants or in the manufacture of prostheses is mainly based on their ability to maintain mechanical, biological, structural, and chemical integrity in achieving safe and effective performance in their presence inside the human body [27]. The biological effects of biomaterials in the human body are evaluated through a set of special tests that include cytotoxicity, genotoxicity and hematocompatibility, immunosensitization tests, in addition to a set of tests of biodegradation, acute toxicity and local irritation, as well as transplantation studies and others. The aim of these tests is to ensure a high level of safety and bio-suitability before the clinical use of substances in medical applications [30]. When designing supporting structures for medical applications and tissue engineering, the importance of biological compatibility lies in cell adhesion and restoration of cellular functions, which plays an important role in ensuring that no unwanted immune response occurs after implantation of the supporting organizational structure, which would lead to incomplete tissue healing or adversely affect the implantation of implants [31]. Jairo et al. made modifications to the surface of a polymeric biomaterial using low-temperature plasma to improve cell adhesion and proliferation [32]. Myers and others transferred the laboratory experiment of biodegradable molopodium from the laboratory to the human body as a biomaterial used in cardiac stenting. With amendments and additions [33]. The article by Myers et al. appears. (2024) a clear superiority in terms of combining convenient mechanical properties and high biocompatibility, which makes molybdenum a promising option for biodegradable heart implants. The Rondón study (2025) focuses on improving the surface compatibility of polymers using plasma treatment, which is suitable for improving the interfaces of implants, but does not cover the mechanical properties required for load-bearing implants. It is advisable to use biodegradable molybdenum for load-bearing implants, and to adopt plasma treatment to improve cellular compatibility in surface polymers.

3.2.2 Corrosion Resistance

Metal corrosion, as a concept, is the opposite of metal extraction, which is damage to the surface of the metal (irreversible). Surface residues such as sulfides, oxides, and some hydroxides transform the metal from a pure metal to a more chemically stable metal. If we put two metals in a solution and the solution was electrified, we would find the least noble metal is the anode of the metal that corrodes, while the Most Noble is the cathode (protected from any corrosion) [34]. Laurian and others have used biomaterials (yttria-stabilized zirconia as well as hydroxides) that enhance bone fusion and increase corrosion resistance [35]. Yehan et al. conducted an article on improving the corrosion resistance of medical stainless steel through the deposition of some nickel alloys, as well as surface modifications represented by plasma immersion ion implantation, thermal spraying or steam deposition technology, and other methods [36]. Finally, it can be said that corrosion is a large and widespread phenomenon that affects all materials, be it metal, ceramic, polymeric or sometimes composite, as well as all environments (air and water at high temperatures and others). The problem of corrosion is an important, economically costly industrial problem that is being experienced all over the world [37]. An article by Medina et al. (2025) is the best in terms of corrosion resistance in medical applications, because they propose advanced hybrid coatings (ZrO2 wag-HA) that significantly enhance corrosion resistance and biocompatibility at once. It is recommended to use advanced packaging such as YSZ and wag-HA, as in the study of Medina et al (2025), to enhance corrosion resistance and biocompatibility in metal implants.

4. Technologies of additional manufacturing of metals

Additive manufacturing, or three-dimensional printing the creation of three-dimensional products by successive layers of materials using a computer, which plays an important role in the era of industry and the advanced development of the metals used. Recently, additive manufacturing technology has attracted great attention to replace traditional methods in various industries such as aerospace engineering, Railways, defense technology, medical implant technologies, prosthetics, etc [38]. Figure 1 represents additive manufacturing processes. Additive manufacturing technology has revolutionized manufacturing across a wide range of industries, making it possible to manufacture products with more complex geometric shapes and reduce waste. Table 1 discusses their advantages, disadvantages, and compatibility of technologies used in manufacturing with materials, their applications, and directions of their development. It predicts the future of additive manufacturing by highlighting potential developments in three-dimensional bioprinting, large-scale three-dimensional printing, three-dimensional food printing, four-dimensional printing, and others [39]. Both traditional manufacturing and additive manufacturing have unique advantages; traditional methods excel in mass production and material diversity, while additive manufacturing excels in rapid prototyping, complex engineering, and customization. Companies can maximize the quality, efficiency, and flexibility of their production by integrating both methods. Where the use of traditional manufacturing allows for mass production, additive manufacturing is good at manufacturing prototypes and complex parts, so the methods have allowed manufacturers more flexible and efficient manufacturing processes. Both methods, therefore, aim to promote innovations and operational excellence. Artificial intelligence-based additive manufacturing course aims at a comprehensive survey to shed light on the basics of the additive manufacturing business and its role in global manufacturing, highlighting the ongoing future challenges and promising prospects towards innovations that can enhance its role in the manufacturing revolution [40].

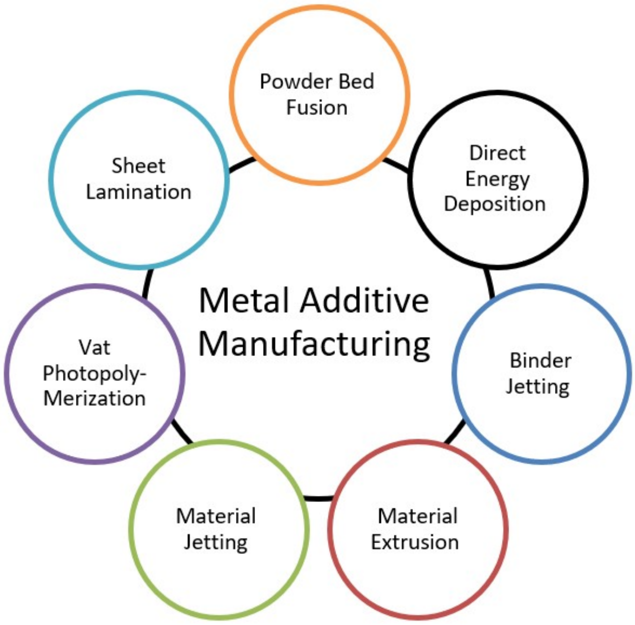

Figure 1. The main processes of additional manufacturing (Direct and indirect).

4.1 Additive manufacturing technologies are commonsense

4.1.1 Selective laser fusion (SLM)

SLM is an additive manufacturing (3D printing) technique used to create complex metal parts with high precision. It uses a high-power laser to fully melt metal powder layer by layer to build solid components. (Janus et al) Conducted a detailed study of the structure and properties of the material using electron microscopy and tensile testing by long-term SLM technique, and the results obtained high mechanical properties. As tensile strength and yield strength, as well as a good ratio of total elongation [41]. Fathipour et al conducted research aimed at improving corrosion resistance through surface modifications (reshaping of fine tracks on the surface), using SLM techniques[42]. (Bulut, et al) Conducted a study on the possibility of determining the ideal laser parameters (power, speed, and intensity settings) used in the manufacture of samples of Super bioalloys to achieve mechanical properties and wear resistance [43]. To simultaneously improve the mechanical properties and biocompatibility, it is recommended to use the Cochrfemnni alloy manufactured with SLM, as in the study of Bulut et al. (2024), due to its good balance between durability and bioresistance, with the possibility of being developed for advanced medical uses.

4.1.2 Electron beam Fusion (EBM)

EBM is a type of additive manufacturing that uses a high-energy electron beam to melt metal powder layer by layer to build 3D metal parts. Zhang et al discussed the difference in mechanical properties between electron Fusion and conventional methods of titanium-aluminum alloys, and the results were that the first method (EBM) achieved better properties in terms of tensile strength and microstructure properties [44]. (Chen et al) demonstrated the results of improving the surface roughness and hardness on the mechanical performance and surface accuracy after LSR laser resurfacing of the Ti-6Al-4V alloy with EBM technology [45]. Hafizoglu et al review the properties of kinetic deformation at high stresses using the EBM technique for Ti-6Al-4V alloys and demonstrate the behavior of the material under the influence of high strength [46].

Table 1. Comparison of biocompatible minerals.

Article	Year	Material	Technology AM	ASTM Standards	ISO Standards	CE Marking
[47]	2025	Ti-6Al-4V	DMLS	ASTM F2924 Requirements for mechanical and chemical properties of the product and its presence by SLM method	ISO 13314 Determination of pressure testing methods to assess their behavior at stress loads	Indirect: Material/test standards that support technical profile and qualification; self-awarded. Any use of MDR clinically requires a course. Full of devices.
[48]	2025	Ti-6Al-4V	SLM / EBM / WAAM / CSAM	ASTM A370 Emphasis on tensile, shock, and hardness requirements	ISO 8692/1 The method of tensile testing of metals is determined at room temperature	Indirect: Mechanical test methods used as qualification guides within the CE link; the QMS track is not independent.
[49]	2025	Ti-6Al-4V	DED	ASTM F3001 The specifications for the manufacture of titanium alloy Ti-6Al-4V are determined using 3d laser fusion, and are used in medical and aerospace applications.	ISO 10993 Criteria for determining the biological safety of medicinal substances.	Direct : When used as a medical device/implant: classified according to MRD, technical profile, clinical evaluation, and risk management before CE marking .
[50]	2024	Ti-6Al-4V	SLM	ASTM F136Laser fusion and used in medical implants	ISO 5832/3 Surgical gases are used to determine the requirements for the mechanical and chemical properties of the Ti-6AL-4V.	Direct: Ensure proof of safety and performance before marking CE, MRD.
[51]	2023	Ti alloys	Various AM	ASTM E8/E8M, Focus on the tensile and elongation properties.	ISO 21432 Determine the method of detecting non-destructive defects of materials using ultrasound.	Indirect: It must undergo the requirements of the MRD pressure test and tensile test.
[52]	2023	Co-Cr, Ti-6Al-4V	LPBF	ASTM F3049ttention to the identification and documentation of materials and parts manufactured by additive technology	ISO /AST ASTM 52907 Determine the requirements for the quality and characterization of metals.	Indirect: must be subject to MRD requirements.
[53]	2025	Ti-6Al-4V, SS316L, Ni-Alloys	DMLS	ASTM G99:Determine the friction wear test method using (Pin-on-Disk).	ISO 7148 Determination of friction and wear parameters and methods for testing non-lubricated (dry) bearings, such as sliding bearings.	Indirect: Emphasize the requirements of the MRD, especially the pedagogy tests.
[54]	2024	Ni Alloys	SLM / EBM / WAAM / CSAM	ASTM F3302, it establishes general requirements for the mechanical, chemical and engineering properties of metals (quality, reliability).	ISO/ASTM 52900 Define the specifications, requirements, and basics of AM operations.	Indirect: It must be subject to the requirements of the MRD.
[55]	2025	SS 316L	DED ASTM	F138/F139These two standards determine the mechanical and chemical properties of stainless steel316l	ISO 5832/1 The method of tensile testing of metals is determined at room temperature	DIRECT: Must undergo clinical evaluation and risk management prior to marketing

If the above articles are compared, an article by Chen et al is recommended. (2025) because it offers the best balance between improving mechanical properties and biocompatibility via laser surface remelting of the Ti-6Al-4V alloy manufactured with EBM technology.

4.1.3 Direct laser felting (DMLS)

Direct laser sintering of metals, which is one of the additive manufacturing techniques and belongs to the family of laser powder fusion techniques, advances in mechanical properties can be observed using DMLS technology with high accuracy and fast turnaround times in manufacturing as well as obtaining complex parts if compared with traditional methods. (Hamnabad et al) provide a comprehensive and accurate overview of DMLS technology and analyze the methods and methods necessary to improve density and accuracy [56]. Wang et al reviewed the method of progress in laser direct filling technology for a group of powders, such as others, and addressed the mechanical properties, methods of improvement, and adjustment of laser parameters [57]. Liu et al review sintering mechanisms in extrusion-based additive manufacturing, showing how temperatures and heating rates affect density and microstructure, while providing insights for the development of improved mechanical properties using precision sintering strategies [58]. The article is prepared by Humnabad et al. (2022), the best in terms of DMLS, recommended for improving mechanical properties, with the need to add surface treatments or encapsulations to enhance biocompatibility in medical applications.

4.2 Effects of additive manufacturing on properties and microstructure.

The main characteristics and disadvantages of the parts manufactured by additive technologies are reviewed and classified into four families: engineering, mechanical, physical, and structural characteristics. Special emphasis is placed on the parameters of the selected am processes affecting the defects and properties of the material, as well as methods of surface treatment, bio-coatings, and others, which allows choosing a design that mainly complies with the requirements [59]. (Afroz et al) conducted an experimental study to analyze some variables, including pores and surface roughness on the fatigue resistance of ALSI10MG alloy using L-PBF technology. the results were the contribution of the above variables to significantly reduce the fatigue life [60]. Pourrahimi and others used the HCAF, HAF techniques to treat surface roughness, where the results were to reduce the surface roughness to 87-89% [61]. (Huang et al) Conducted a comprehensive review of the stages of microstructure evolution and residual stress through the latest methods of analysis using additive techniques [62]. (Ginkalp et al) Conducted an intensive study of the Ti-6Al-4V alloy using selective laser melting technology to obtain a density close to the theoretical density as well as the extent to which defects affect the fatigue and cracking properties [63]. Compared to the above articles, we find that the best article is (Huang et al. 2025) because it is the only one that comprehensively discusses the impact of additive manufacturing on microstructure, residual stresses, and mechanical properties using advanced analysis.

Table 2. The comparison of commonly used biomaterials and strategies for improving the mechanical and surface properties necessary for biocompatibility.

Material	Article	Year	Surface traitment	Heat treatment / residual stress	The main results
SS 316L	[64]	2023	Mechanical grinding to smooth the surface (SBD)	High residual stresses caused by repeated thermal cycles during SLM printing	Reducing surface stresses due to the transformation of surface grinding SPD into a nanostructure
Ti-6Al-4V	[65]	2024	Chemical corrosion of the surface of the protrusions + Spray blasting	Increase optional performance , improve HIP fatigue resistance	Increased fatigue resistance of 50-60%
Ti-6Al-4V	[66]	2023	Full coverage of the LPBF , surface treatments	Review of thermal protocols and their impact on the structure	Demonstrates the balance between microstructure and stresses
Nickel alloy / Co-Cr	[67]	2023	Revision (mechanical finishing) is applicable to Co-Cr	To relieve stress (HT) and improve microstructural properties	The variation of the Protocols of the properties of the microstructure of the Alloy, a significant effect on stresses.
Magnesium alloys	[68]	2024	Shot peening, cold rolling to generate surface compressive stresses.	HT (inter-pass cooling and others) to control stress	Refine the grain, improve fatigue resistance and allow the removal of efforts.
Magnesium alloys	[69]	2024	Analysis of fast-hardening microstructure without surface treatment.	————————	An oriented microstructure is formed as a result of rapid solidification during printing The appearance of distinct dendritic structures - fine control of grain size and fine structure.

Table 3. A comparison of biomedical applications, techniques used, and study models with their most prominent results.

Ref.	Year	Material type	Study Type	Biological Model	Application	Key Findings
[70]	2022	3D-printed Titanium	In vivo	Dogs	Dental implants	Enhanced osseointegration
[71]	2025	Ti+Bioactive Glass	In vivo	Rats	Bone implants	Promoted bone growth
[72]	2024	Magnesium alloy	Numerical simulation	None	Solidification modeling	Insight into rapid solidification microstructures
[73]	2023	Biodegradable Mg	Review study	Multiple (review)	Orthopedic fixation	Promising but needs surface modificatons
[74]	2022	WE43 Mg (LPBF)	In vitro + In vivo	Rabbits	Porous bone scaffolds	
[75]	2022	Porous Mg (AM)	In vitro + In vivo	Rats	Anti-infection implants	Controlled degradation, good bone growth
[76]	2025	316L SS (AM)	In vivo	Wistar rats	Orthopedic implant	Reduced infection, supported bone integration
[77]	2023	316L SS (AM)	Engineering evaluation	None	Biomedical implants	Improved hemocompatibility and osteoinduction
[78]	2023	Nanostructured 316L SS	In vitro	Osteoblast cells	Enhanced biofunctionality	Mechanical characterization only Boosted cell activity and anti-fouling properties

They give an integrated view compared to the rest of the articles that focus on separate elements. It is recommended to combine precision control techniques of manufacturing parameters with advanced structural analyses to reduce residual stresses and porosity, improve roughness, and mechanical properties in metal parts manufactured by three-dimensional printing.

5. Optimization strategies

Computational methods, material selection, and design have also played a pivotal role in improving the performance of biomaterials [79]. In addition, innovations in Material Design skills have significantly enhanced the biocompatibility, functionality and mechanical performance of implants in general, paving the way and expanding the circle of uses in biomedical applications [80]. The surface properties of materials, being the first line that directly touches biological tissues, contributed to a significant impact on their functioning in the body [81]. The Table 2 below represents his comparison of commonly used biomaterials and strategies for improving the mechanical and surface properties necessary for biocompatibility.

6. Applied examples and clinical studies

A study proves that the improvement of the structure and surface in printed Ti implants plays a prominent role in biocompatibility and intrabody organ integration.

- (Lee, et al) AM + DED) prints appear that contribute to increased hydrosphilicity, improve wear resistance and reduce the release of metal ions, contribute to faster bone fusion and good atherosclerotic growth, without strong toxicity in vital tissues [70].
- (Lee , et al) Ti + bioglass composite medical implants have shown effective results in the growth of the bones that surround the implant [71].
- (Tourret, et al) Demonstrates the development of a microstructure in the Mg implant due to rapid hardening during printing, directly affects the mechanical and functional performance [72].
- (Thomas, et al) A review of biodegradable Mg properties, surface challenges, with biocompatibility improvement strategies [73].
- (Liu, et al) The improved porosity in Mg has been proven to aid bone growth and accelerate the effectiveness of bio-Fusion (LPBF) [74].
- (Xie, et al) Mg implants with surface enhancements, such as nanocoatings, contribute to reducing infection and enhancing biocompatibility [75].
- (Pttanaik, et al) developed a bone implant from 316L stainless steel using additive manufacturing, with surface modification to improve the results were hematocoietic and cellular compatibility, bone stimulation as well as the absence of toxicity in the liver or kidneys [76].
- (Prakrathi, et al) LDED technology produces a smooth structure or S alloys.S 316L has a hardness of hv 224 and a corrosion resistance similar to conventional bioalloys, and is similar to a conventional alloy when evaluated using Hanks solutions [77].

- (Erdogan, et al) Surface anodizing generates a nanostructure that enhances the activity of bone cells and is considered an antibiotic and supports biocompatibility of bioalloys [78].

It is necessary to link the challenges and improvements as well as the results for bioalloys produced using additive manufacturing techniques, through which medical products and devices are produced and developed, as in Fig. 2 . As shown in Table 3 show some comparisons between additive manufacturing techniques and materials used in addition to the field of medical applications. Finally, Table 4 shows ïntegrated strategies for optimizing the outputs of additive manufacturing integrating optimization of operating parameters, post-processing, alloy design and computer modeling towards the path of accelerating manufacturing processes with clinical translation"

Table 4. Integrated strategies for optimizing the outputs of additive manufacturing.

Process parameter optimization	**Post-processing treatments**	**Alloy design**	**Computational modeling**	**Clinical translation**	**Key Findings**
[4] (hot rolling, torsion, extrusion)	[82] surface treatments	[4] *cu_zn* alloy design	[83] modeling of human-prosthetic	[4] it has cellular compatibility and bone differentiation	Enhanced osseointegration
[82] porosity control via additive technology.	[6] coatings	[16] metal alloy design	[18] simulation of the diffusion process	[84] clinical effects have a close association with toxicity.	Promoted bone growth
[14] control of manufacturing processes.	[11] multifunctional coatings	[19] multiple alloys	[52] numerical simulation	[85] within the standards and regulations.	Insight into rapid solidification microstructures
[18] deployment process improvements.	Biodegradable Mg, [Laser surface treatment]	[26] Zn alloys are of a special character	[59] modeling the classification of defects	[16] direct clinical application.	Promising but needs surface modifications
[19] porosity control.	[20] heat treatment.	[28] an alloy of Mg, Zn	[62] modeling stress analysis	[21] application in medical implants.	
[21] adjust porosity by AM.	[22] nano-anodic coating	[83] Polymeric compound	[65] rapid thermal analysis as a computational	[22] enhance the functions of osteocytes.	Controlled degradation, good bone growth
[25] Adjust laser parameters.	[27] polymer coating	In vivo	[67]computer models of microstructure properties	[25] biodegradable for medical devices.	Reduced infection, supported bone integration
[27] purification of Mg, addition of Zn.	[83] processing modifications	——	[68] modeling within the review	[27] animal and clinical study.	Improved hemocompatibility and osteoinduction
[28] innovative powder approach.	[30] superficial improvements	——	[69] simulation models of rapid hardening	[80] biocompatibility and bone implants.	Mechanical characterization only
——-	[51] subsequent treatments	——-	[73] a review involving computational surface models	[81] focus on medical implants.	Boosted cell activity and anti-fouling properties
——-	[80]laser modifications	——-	[81] process modeling for parameter optimization	——-	——-

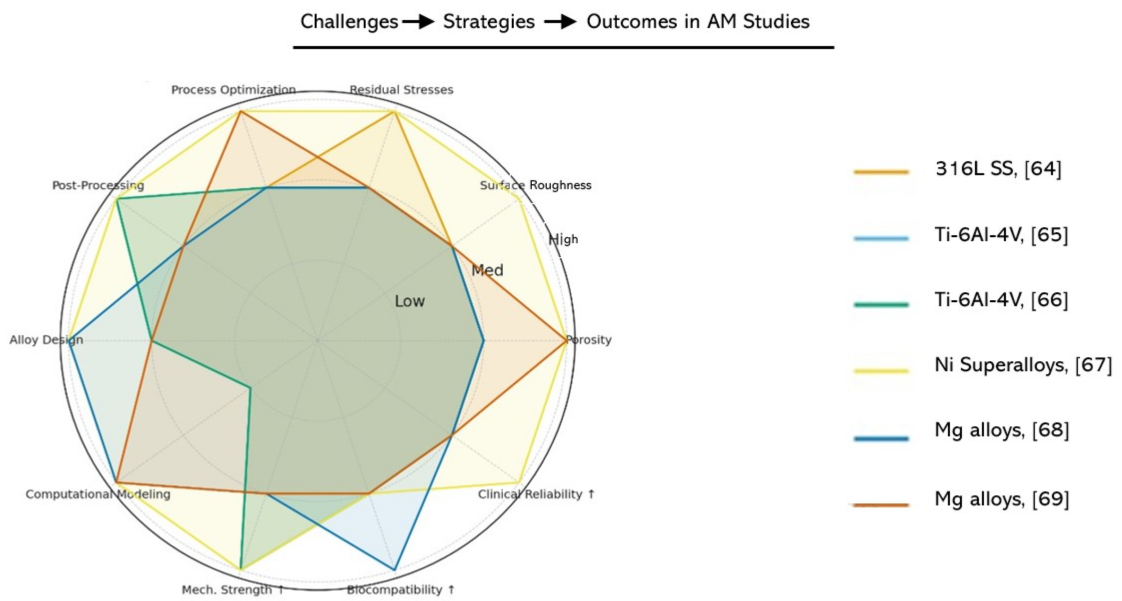

Figure 2. Map of improving bioalloys manufactured with additive technology, turning challenges into results.

7. Conclusions and future suggested approaches

The strategies employed to enhance the properties and functional performance of biocompatible metals produced via additive manufacturing (AM) represent a pivotal advancement in the development of modern medical applications. Experimental and clinical evidence has demonstrated that approaches such as surface modification (e.g., polishing or bio-coating), precise control of printing parameters (including power, speed, and spacing), and post-processing heat treatments significantly contribute to minimizing microscopic defects, reducing residual stresses, refining microstructure, and thereby improving both mechanical performance and biocompatibility. Furthermore, the incorporation of nanomaterials or bioactive elements, either within the bulk material or on the implant surface, has opened new avenues for modulating cellular responses and enhancing osseointegration. The integration of digital modeling and computational simulations further enables the design of patient-specific implants that meet anatomical and functional requirements with high precision. Collectively, these advanced strategies not only improve the clinical outcomes of metallic biomedical implants but also increase the reliability and efficiency of AM-based medical devices. As research in this field continues to evolve rapidly, driven by the growing demand for personalized and high-performance healthcare solutions, additive manufacturing is expected to play an increasingly central role in the future of regenerative and precision medicine.
Focusing on the advanced and emerging trends in the field of additive manufacturing, which is expected to witness rapid developments enhanced by the growing need for highly efficient personalized solutions and methods in healthcare, especially the role of artificial intelligence and machine learning in improving additive manufacturing processes through accurate forecasting of parameters, detecting defects and gaps, and ensuring high quality over time. The application of the four-dimensional printing(4D) concept opens new horizons and is a transformational step towards the development of dynamic implants capable of responding to various physical and biological stimuli, allowing more personalized medical solutions in adapting to the body's internal environment. In addition, the exploration of biodegradable minerals such as molybdenum (Mo), magnesium (Mg) and zinc (Zn) represents a promising path to the creation and manufacture of implants that gradually degrade inside the body to support the process of tissue regeneration, reducing the need for additional surgical intervention. In doing so, these future strategies contribute to enabling manufacturing technology in addition to becoming a leading focus in modern medicine and biometallics applications in regenerative medicine and precision medicine of the future.

Authors' contribution

All authors contributed equally to the preparation of this article.

Declaration of competing interest

The authors declare no conflicts of interest.

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Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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