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Review Article

Tribocorrosion of 3D printed dental implants: An overview

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الملخص

مع التقدم في علوم طب الأسنان والحاجة المتزايدة لتحسين صحة الأسنان، أصبح من الضروري تطوير مواد زراعة جديدة تمتلك خصائص هندسية وميكانيكية وفيزيائية أفضل. البيئة الفموية هي بيئة أكالة، كما أن الحركة النسبية بين الأسنان تجعل البيئة أكثر عدائية. لذلك، يجب دراسة التآكل المشترك وعلم الاحتكاك المعروف باسم تآكل الغرسات. إن الأشكال المعقدة لزراعة الأسنان ومتطلبات الأداء العالي لهذه الغرسات تجعل التصنيع صعبا من خلال عمليات التصنيع التقليدية. مع ظهور التصنيع الإضافي أو الطباعة ثلاثية الأبعاد، أصبح تطوير الغرسات أمرا سهلا. ومع ذلك، فإن المتطلبات المختلفة مثل خشونة السطح، والقوة الميكانيكية، ومقاومة التآكل تزيد من صعوبة تصنيع الغرسات. تستعرض الورقة الحالية الدراسات المختلفة المتعلقة بالغرسات المطبوعة ثلاثية الأبعاد. كما تحاول الورقة تسليط الضوء على الدور الذي يمكن أن تلعبه الطباعة ثلاثية الأبعاد في مجال زراعة الأسنان. هناك حاجة إلى مزيد من الدراسات التجريبية والعددية لاستنباط الظروف المثلى لغرسات الطباعة ثلاثية الأبعاد لتطوير الغرسات ذات الخصائص الميكانيكية والتآكل والبيولوجية المحسنة.

الكلمات المفتاحية: زرع الأسنان؛ الطباعة ثلاثية الأبعاد؛ تآكل؛ علم الاحتكاك؛ التصنيع المضاف؛ التوافق الحيوي؛ التآكل الثلاثي؛ التركيب السطحي؛ الخصائص الميكانيكية

Abstract

With the advancements in dental science and the growing need for improved dental health, it has become imperative to develop new implant materials which possess better geometrical, mechanical, and physical properties. The oral environment is a corrosive environment and the relative motion between the teeth also makes the environment more hostile. Therefore, the combined corrosion and tribology commonly known as tribocorrosion of implants needs to be studied. The complex shapes of the dental implants and the high-performance requirements of these implants make manufacturing difficult by conventional manufacturing processes. With the advent of additive manufacturing or 3D-printing, the development of implants has become easy. However, the various requirements such as surface roughness, mechanical strength, and corrosion resistance further make the manufacturing of implants difficult. The current paper reviews the various studies related to3D-printed implants. Also, the paper tries to highlight the role of 3D-Printing can play in the area of dental implants. Further studies both experimental and numerical are needed to devise optimized conditions for 3D-printing implants to develop implants with improved mechanical, corrosion, and biological properties.

Keywords: 3D printing; Corrosion; Dental implants; Surface texturing; Tribocorrosion; Tribology

Brief overview of dental implants

Around 2500 BC, ancient Egyptians used gold ligature wires to stabilize periodontally affected teeth. Their ancient manuscripts and texts offer fascinating insights into their dental practices, referencing not only the use of gold ligature wire but also providing intriguing accounts of toothaches and related oral health concerns prevalent during that time.[1] Around 500 BC, the Etruscans showcased their remarkable

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dental craftsmanship by creating customized soldered gold bands sourced from animals, which served to restore oral function in humans. Additionally, they displayed their resourcefulness by crafting tooth replacements using oxen bones. During the same era, the Phoenicians also demonstrated their dental ingenuity by employing gold wire as a means to stabilize teeth affected by periodontal issues. Advancing further in history, around 300 AD, these innovative societies continued to impress by carving tooth replacements out of ivory and ingeniously stabilizing them with gold wire, resulting in the creation of fixed bridges. As we delve deeper into the annals of time, the Mayan population emerged as pioneers in dental implants, with evidence dating back to roughly 600 AD. The Mayans skillfully utilized pieces of shells as implants, effectively replacing mandibular teeth, leaving an enduring legacy in the field of dental implantology and underscoring the progressive nature of early dental practices.[2–4] During the 1930s, Dr. Alvin and Moses Strock, in their pioneering efforts, conducted experiments using orthopedic screw fixtures made of Vitallium, a chromium-cobalt alloy. Inspired by successful hip bone implants, they ventured to restore individual teeth by implanting these screws in both humans and dogs. The Vitallium screw proved to be an effective anchor, providing support for replacing missing teeth. Their groundbreaking work was recognized for choosing a biocompatible metal for human dentition, marking a significant milestone in the history of dental implantology.[5] During the 1950s, Dr. Bodine conducted observations on several patients in the armed forces and noticed a significant evolution in the framework design of dental implants. The new design featured a more streamlined approach, requiring fewer struts or girders. He also strategically positioned the screw holes in areas of the bone with the greatest strength and thickness, ensuring improved stability and support for the dental implants. These advancements in design and placement marked a notable step forward in enhancing the success and effectiveness of dental implant procedures.[6] Starting from the mid-1980s, the prevalent choice among dental clinicians for dental implants were the endosseous root-form implant. Coating the dental implants with calcium phosphate increases the osseointegration in the implants.[7] However, use of titanium alloys in dental implants induce stress-shielding due to the high modulus of elasticity.[8] The selection of a specific endosseous implant the system was influenced by various key factors, such as its design, surface roughness, prosthetic considerations, ease of insertion into the bone, cost-effectiveness, and long-term success rates. These considerations played a crucial role in determining which implant system was preferred over others, as clinicians sought to achieve optimal outcomes for their patients during this period of dental implant evolution. On the other hand, at the moment, tooth loss or other medical complications in theoral cavity are unfortunately very common not only in the elderly age but also in adults or young people, requiring a rapid response from the clinical and engineering community. Hence, at the moment, several different implants are produced and inserted in the human oral cavity, according to the clinical conditions of the patients, medical procedures, specific necessities, and so on.[9] In particular, the number is growing day by day,[10] thanks to high success rate[11] and reliability but also thanks to the progressive development of technologies and competencies adopted for avoiding unpleasant events such as infections or mechanical failures, protecting thus the functionality of the prosthesis. In that sense, the structure, material, and topography of the implant are key aspects for its survival, being directly correlated with the process of osseointegration.[12,13] Unsurprisingly, the research is going towards new trends in terms of biomaterial used and the treatments applied, the design of the implant and so on, representing concrete opportunities for implant improvement,[14] satisfying, in this way, the necessities and requests of the single individual.

In this scenario, to our knowledge, the current state of art provides review articles focused on the fabrication methodologies[15,16] and applications[17] of additive manufacturing for dental implants. On the other hand, the tribocorrosive behavior was documented by Saha and Roy,[18] by Villanueva et al.[19] but only for conventional fabrication methods and by Awasthi et al.[20] referred to general orthopedic tools. Hence, in this manuscript the authors aim to provide firstly a deep background of dental implants in terms of structure, topography and material, presented respectively in sections 2, 3 and 4. Successively an insight into the biotribocorrosion field is proposed, for both conventional and additive manufacturing, in which the main literature results will be discussed. Section 5 will highlight these aspects. Lastly, the conclusions together with the future developments of this ongoing field.

Dental implant structure

The structure of a common dental implant is essentially composed of three elements[21] as the implant, which is coupled with the abutment by mechanical workings or a fixing screw, and the crown which represents the artificial tooth and corresponds to the uppest zone of the total system. More precisely, the coupling abutment-implant is realized by hexagonal internal or external connection or by morse taper fixing as underlined in Figure 1. The main difference is that the hexagonal internal requires the fixing screw whereas the other ones the conical keying. In any case, other junctions are common such as the octagonal, conical, or trilobe.[22] Concerning, instead, the connection with the prosthesis, the screw is the most adopted choice but, as shown by Cicciù et al.,[23] the cementation technique provided a more homogeneous distribution of the loads.

Nevertheless, innovative prototypes are diffused, as shown by Chen et al.[24] who realized a new design providing a no-gap mechanism and sealing. The scope is to reduce as much as possible the potential micromovements generated by occlusal forces since they are strictly correlated with the stability of the implant as well as the formation of micro gaps where bacteria may penetrate and locate, leading to inflammations in the proximity of the bone tissues. Another opportunity is offered by Sugiura et al.[25] who noted that the tilted implants had a lower maximum extent of micromotion than axial implants. Regarding the design, instead, the implants are divided with respect to the geometrical design in terms of total length, head diameter, and the type of thread, each one relevant to stress distribution and

Figure 1: Representative images of commercial implants connections: morse taper (a), external hexagonal (b) and internal hexagonal with fixing screw (c). CAD files realized in SolidWorks 2022.

long-term survival.[26] In Table 1 some examples with common dimensions and thread patterns are reported.

The diameter and the length are important variables in biomechanical couplings as stated by Li et al.[27] and by Himmlová et al.[28] in the way that for longer and wider implants the stress and the strain were lower.

Nevertheless, short implants (Figure 2a), when the length is <8 mm, or ultrashort (Figure 2b), when the length <6 mm, are at the moment center of discussion in the scientific community,[29−31] since they outline a valid alternative to the first ones,[32] as demonstrated by De Stefano et al.[33,34] being though less invasive with a lower probability of inflammation and, at the same time, faster and cheaper as surgical treatment.[35]

Analogously, the thread types (Figure 3) and features in terms of depth, pitch, face angles and width (Figure 4), are also crucial for stress distribution.[36] For instance, the number of threads and their depth are important because the more they are, the more are spot contacts,[37] where the bone can grow and develop. In this circumstance, new patterns have been introduced as done by Paracchini et al.[38] Indeed, they demonstrated, by a FEM analysis, that their *nest shape* structure showed lower stress and strain, above all in the interface cortical bone-neck of the implant.

Finally, in the case of edentulism, i.e., when the patient misses all teeth, a recent technique involves the use of an arch, most of the times in resin or CrCo alloys,[39] and just four implants (Figure 5) positioned two vertically in the incisive and two obliquely (18−45° respect to the vertical axis) molar regions, in accordance with the Paulo Malo concept.[40]

The geometrical features as much as the design of all the medical tools were provided by MaCo International (Industrial area-Buccino-Italy).

Table 1: Most common geometrical dimensions and thread patterns of dental implants.

Diameter Ø [mm]	Length L [mm]	Thread patterns
2	8	Buttress
3	10	Reverse Buttress
4	11.5	V-shape
5	13	Sinusoidal
6	16	Square

Surface topography and biocompatibility in dental implants

Biomechanics explores the intricate interactions among body tissues and organs, along with the forces they encounter. This field investigates how biological tissues respond under applied loads. Evaluating the biocompatibility of dental implant materials involves a thorough examination of their response to bone and soft tissue. Creating a reliable seal at the implant-soft tissue interface is vital to isolate the implant and bone from the oral environment. Implant biomechanics is an evolving area of research, with significant implications for various aspects of implant treatments. Although some evidence exists on bone response to loaded implants, our understanding remains limited due to a lack of fundamental studies combining implant biomechanics with bone biology. This gap has hindered a comprehensive interpretation of extensive clinical data amassed over the past three decades.[41] The integration of natural teeth and dental implants to support bridge is seems feasible, despite their distinct mobility characteristics and potential biomechanical challenges. The key to this compatibility lies in the screw joint's flexibility, enabling the natural tooth to move downward without subjecting the implant to undue pressure or causing the screw joint to excessively open. This flexibility ensures a harmonious functioning of the combined dental elements in the bridge structure.[42] The dental field faces a complex challenge in achieving successful tooth replacement without compromising bone health. Despite the availability of various dental implant types and accessories, their ability to fully restore masticatory function remains limited and controversial.[43,44] Therefore, it becomes crucial to understand and assess the stresses that dental implants undergo. To achieve this, researchers are exploring non-invasive methods to evaluate the impact of various parameters and implant positions in the mandible, allowing for a comprehensive assessment without incurring the costs and risks associated with actual implantation procedures.[45,46] A prominent area of interest is the study of cell-implant surface interactions, as understanding these interactions in detail can pave the way for the development of innovative surface treatments.[47] Cell growth and function during the initial stages of osseointegration is influenced by topographical characteristics, surface roughness, energy, and chemical composition impacting the longevity of the prosthesis, because strictly linked to the

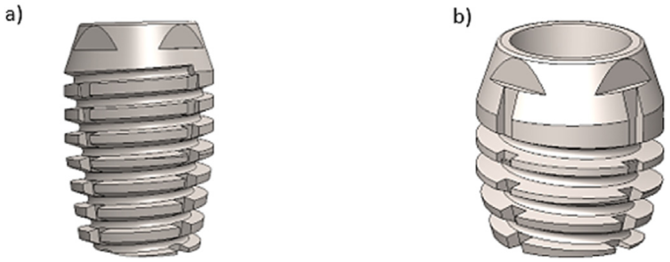


Figure 2: An example of commercial short implant (a) of diameter 4.6 mm and length 7 mm and ultrashort implant (b) of diameter 4.6 mm and length 5 mm. CAD files realized in SolidWorks 2022.

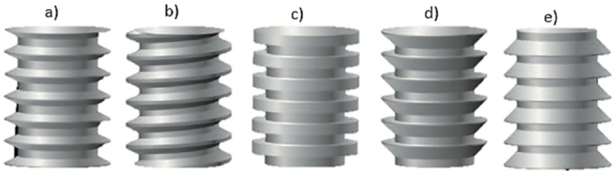


Figure 3: Type of threads: V-shape (a), Sinusoidal (b), Square (c), Buttress (d), Reverse Buttress I. CAD files realized in SolidWorks 2022.

Figure 4: Geometrical features of the thread. CAD files realized in SolidWorks 2022.

process of osteointegration,[48] the biological process by which the formation of bone tissue around the implant surface happens.[49] The surface characterization can be performed by different techniques such as confocal technique or interferometry, which is commonly adopted in dentistry[50] since its accuracy and range resolution of order of nanometers,[51,52] but also scanning electron microscopy and stylus profilometry are valid alternatives.[53] In any case, describing a roughness surface is not a trivial task since the great amount of roughness parameters (height, spatial, hybrid, functionals) as much as the different scales of investigation which may yield diverse outcomes. In that sense, in dentistry, the topography should be divided into three levels[54]:

1. Macro (10 μm-1mm) for the contact between bone surface and implant.
2. Micro (1−10 μm) for the contact between mineralized bone and implant.
3. Nano (less than 1 μm) for the adsorption of proteins and adhesion of osteoblast cells.

Moreover, among the multitude of the parameters reported in the literature,[55] only the arithmetical roughness was demonstrated to be correlated with the osseointegration process.[53] More precisely it should be included in the range 1−2 μm for an appropriate bone growth (Figure 6). Hence, increasing roughness results in a better biological response[56] since for this interval there is a

Figure 5: Four-implants supported by an arch in a human mandible. CAD files realized in SolidWorks 2022.

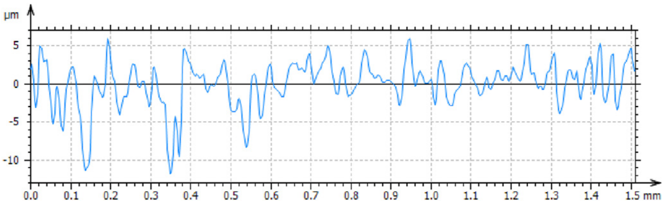


Figure 6: Topography of top surface of commercial dental implant surface with R_a 1.5 µm in horizontal direction.

right equilibrium between osteoblasts, which are responsible for the construction of new bone matrix, and osteoclasts, responsible for the destruction of old bone matrix.[57]

On the contrary, rougher surfaces are more sensitive to bacterial attack.[58] In particular the presence of microorganisms represents a deep issue among the researchers because it could compromise the efficiency of the implants by favoring infections, and diseases, not only in the implants (*peri-implantitis*) but also in the gingiva (*gingivitis*), and near the bone (*peri-odontis*). The phenomenon is referred to as *microbially induced corrosion* (MIC)[59] and it is the cause of corrosion for about 1/3 of the metallic corrosion cases. Therefore, for the optimal design of implants is crucial to consider not only the topographical aspect but also the biological response and thus the cell behavior to avoid a premature failure.[60] The biological aspect does not involve only the microbial factor but every bio-mechanism that occur after and during the implantation of the appliance: ions diffusion, the presence of water molecules, protein adhesion, and all the other examples of dynamic interactions between implant and surrounding tissues which occur at the material surface (Figure 7).

These natural processes depend on the clinical situation of the patient, and they are also time-dependent since during the implant life cycle the topography and the oral environment are constantly modified.[61] In this light, various surface modification methods have been created to enhance the osseointegration of dental implants made from commercially pure titanium.[62,63] These approaches aim to increase primary stability and reduce healing time. The surface properties of implants, including their morphology, roughness, oxide layer thickness, chemical composition, impurity level, and types of oxides, are all dependent on the specific surface treatment process used.[64,65] At the moment, essentially two kind of techniques can be adopted: physical such as plasma spraying, sputter deposition, magnetron sputtering, etc. and chemical such as sol—gel or electrochemical deposition.[66] Extensive research through in vivo and in vitro studies has demonstrated that the characteristics of dental implant surfaces significantly influence cell activity, leading to changes in cell differentiation, proliferation, and extracellular matrix formation. The bioactivity, defined as ability of an external object to interact with the biological environment to enhance the appropriate biological response, results even crucial for the longevity of the prosthesis. Any material cannot be considered as completely inert and therefore biological interactions always occur. The aim of researchers and engineers is to promote positive interactions and to avoid toxic reactions, safeguarding at the same time the mechanical performance

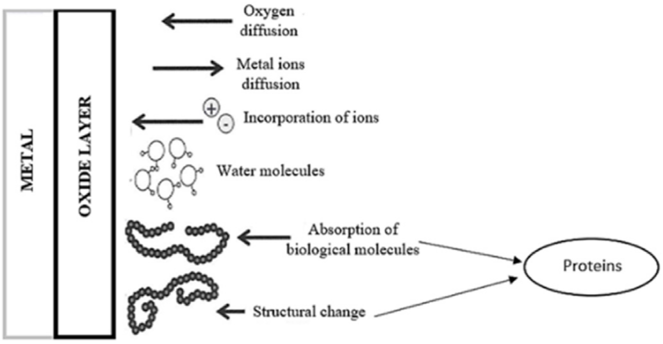


Figure 7: Examples of interactions between implant and surrounding biological environment.

of the device. In this light, acid etching, sandblasting, and electrochemical treatments are more effective than plasma spray or laser treatment.[67,68] However, there is a lack of consensus among researchers regarding the optimal surface type and implant shape. Conical implants, in particular, require higher installation torque compared to cylindrical dental implants.[69] Further research is needed to enhance our understanding of cell-implant surface interactions and to analyse the impact of various parameters on protein interactions, bone formation stimulation, and the development of individualized therapies for critically considered patients. Dental implants offer the ability to chew food, maintain and strengthen the bone structure and patient gain the confidence to smile. They also preserve bone structure which provides additional protection for the existing teeth.[70] The degradation of implant materials and the subsequent release of particles or ions, along with their impact on complications related to dental implant therapy, have been extensively documented. Any lack of conformity in this regard raises significant concerns about patient safety. The physicochemical characteristics of wear debris not only interfere with biological responses but also enable these particles to permeate cell membranes and be absorbed by the cells. Figure 8 shows a schematic representation of the causes and concerns associated with material degradation and particle release in dental implants.

Dental implant material aspects

Dental implants have been constructed using an extensive array of materials, encompassing metals, ceramics, and polymers. Metals as the most traditional materials, have historically been the earliest and most widely employed form of material for dental implants, and to this day, they continue to be the prevailing choice in implant dentistry. There are various types of ceramics material available for dental implants including: Hydroxyapatite, Alumina, Beta tricalcium phosphate, etc. Polymers play a significant role in fulfilling specific requirements for temporary or provisional dental restorations and certain implant components. Figure 9 below represents the different types of materials used for dental implants.

In biomedical field, high molecular weight biocompatible polymers are typically considered non-degradable and categorized as bioinert. However, concerns regarding toxicity may arise from the leaching of low molecular weight plasticizers and additives associated with these polymers. Therefore, it is imperative to thoroughly characterize the grade of polymer being utilized. To enhance the osseo conductive properties and surface roughness of polymers, they can be subjected to coating and blending processes with bioactive particles. Consequently, recent research endeavors have predominantly focused on the modification of polymers by

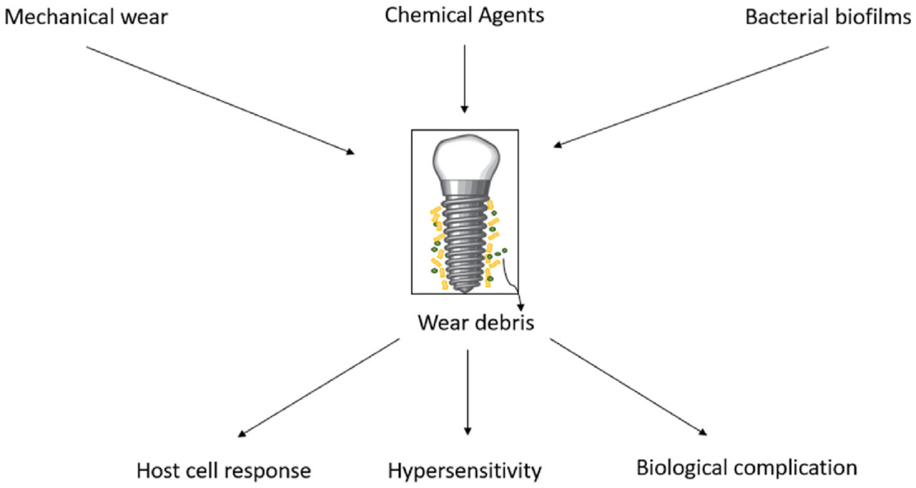


Figure 8: Schematic representation of the causes and concerns associated with material degradation and particle release in dental implants.

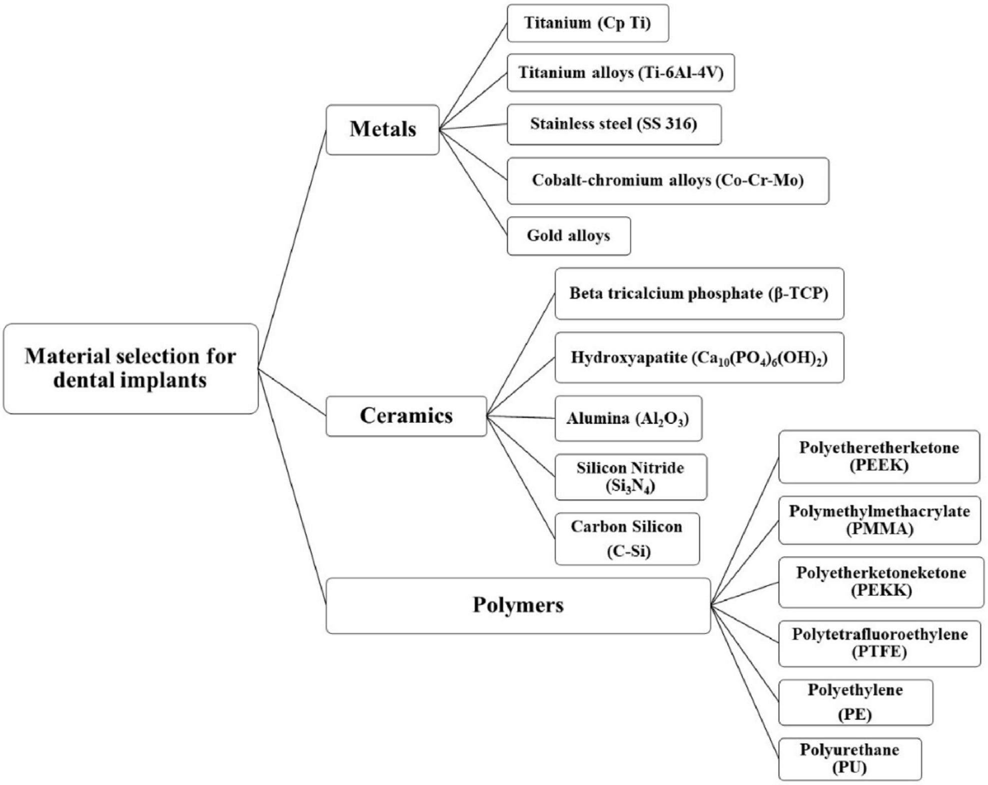


Figure 9: Different materials used for dental implants.

incorporating nanosized particles and creating nanolevel surface topography.[7,8]

Within the domain of dental implants micro design modifications are made to the implant surface while preserving the macro design features. These alterations encompass adjustments to the surface roughness, topography, composition, and other intricate aspects of the implant. Diverse surface modification strategies, such as physical, chemical, and thermal treatments, are employed to achieve these changes.[71] Some treatments introduce micro-sized features on the implant surface, while others create nanotexturing or a hybrid of micro and nano features on the implants. Numerous studies suggest that, when compared to a smooth surface, an optimal micron-scale roughness has the potential to improve osteoblast differentiation and promote bone-implant contact in vivo.[72,73] Early modifications of dental implants in the latter part of the last century mainly concentrated on increasing surface area through micro-texturing techniques, which proved beneficial in enhancing bone-implant contact.[74–76] An alternative approach to creating biomimetic surfaces involves utilizing charge effects and cell signaling through submicron or nanoscale topography, sometimes combined with micron-scaled surfaces. The objective is to establish a close connection between tissues and implants, facilitating controlled, predictable, and guided tissue healing. The literature describes several innovative nanostructured materials, including titanium-based nanotubes and other bioactive ceramic materials, which hold significant promise for modifying implant surfaces. Nanostructured surfaces, characterized by nanoscale pores, irregularities, or spike-like nanofeatures on titanium implants, play a pivotal role in mimicking the natural structure of bone or soft tissue. This enhancement in imitation facilitates the healing process, promoting more effective tissue integration and regeneration. Surfaces featuring nanoscale topography play a crucial role in the initial stages of integration, influencing processes such as protein adsorption, blood clot formation, and cellular behavior after implantation. These early events exert a substantial and influential impact on the migration, adhesion, and differentiation of progenitor cells. Furthermore, it has been observed that nanostructured surfaces can regulate the differentiation pathways, guiding cells towards specific lineages and ultimately influencing the nature of peri-implant tissues. Human bone exhibits a hierarchical composition, encompassing various mechanical, biological, and chemical functionalities at different levels. This hierarchy comprises elements at the macro, micro, sub-micro, nano, and sub-nanoscale levels. At the macroscale, the bone's overall shape, marrow spaces, and trabeculae are observed. At the microscale, features such as osteons, lacunae, lamellae, canaliculi, erosion cavities, and resorption sites, as well as cells like osteocytes, osteoblasts, and osteoclasts, are measured. The building blocks of bone, namely collagen fibers and hydroxyapatite nanocrystals, are considered as nano or sub-nanostructures. Blending micro and nanoscale modifications of implants based on scaling principles has demonstrated significant benefits in promoting osteogenic cell growth.[77] By replicating the hierarchical structure found in natural bone tissue, this approach creates a random structure that positively influences the performance of the implants, leading to improved outcomes. According to the literature, micro-texturing applied to implants creates structures similar in size to bone resorption pits and cells.[78] Consequently, the micron topography on the surface can provide mechanical interlocking and support cell differentiation, but it may hinder cell spreading and proliferation as cells tend to stay within the microgrooves.[79,80] In contrast, nanoscale topography typically promotes cell adhesion, proliferation, and differentiation, possibly because of its resemblance in size to extracellular matrix proteins and membrane receptors. The synergistic effect of combining micro and nano-scale surface topography on implant materials reveals that this multi-scale hierarchical hybrid surface effectively addresses the negative impact of microscale topography on cell spreading.

Surface coating for dental implants

Integrating bioactive materials onto robust biometals combines the bone-bonding capability of the bioactive materials with the mechanical performance of the biometals. These bioactive materials include hydroxyapatite (HA), magnesium-containing mixed coatings, graphene, various proteins, and more.[81–85] The thickness and roughness of the coatings can influence the chemical inertness, cell adhesion, and antimicrobial properties of the dental implant surface.

From a commercial perspective, plasma-sprayed hydroxyapatite (HA) emerges as the prominent choice, given its widespread popularity. These coatings, post-processing, often exhibit partial amorphous characteristics and may contain other crystalline phases in addition to HA. Notably, both plasma-sprayed HA and other bioactive ceramic coatings have been proven to promote enhanced bone apposition when compared to uncoated metal implants, making them highly valuable options for various implant applications. Nano-hydroxyapatite can be used as a single coating or combined with collagen, bioglass, or titanium dioxide in a composite manner to mimic the bio-environment of natural bones.[86,87] When particles are reduced to the nano-size scale, their specific surface area and adsorption ability significantly increases. Over time, nano-hydroxyapatite coating consistently enhances bone bonding with dental implants compared to a typical dual acid-etched surface.[88,89] Breding et al.[90] conducted a study to assess the osseointegration of Titanium (Ti) implants with and without nano-hydroxyapatite (HA) coatings using the real-time polymerase chain reaction (RT-PCR) method. The surface morphology results, obtained through electron microscopy, revealed the presence of elongated particles on the HA-coated implants, indicating the presence of HA nanocrystals. Additionally, the surface roughness of the HA-coated implants was found to be lower, suggesting the presence of smaller surface structures. The RT-PCR results on osteoblast, osteoclast, and proinflammation markers exhibited significant differences between the HA-coated implants and non-coated implants. According to the authors, the incorporation of HA nanocrystals as implant coatings resulted in superior osseointegration compared to the non-coated implants.

Wennerberg et al.[91] investigated the stability of hydroxyapatite (HA) nanoparticles coated on titanium (Ti) implants. The researchers introduced a total of 20 threaded and turned titanium micro-implants, each coated with HA nanoparticles, into ten rats for experimental purposes. To trace the HA nanoparticles, they labeled 16 of these implants with calcium 45 (45Ca). Over the course of the eight-week experiment, radioactivity measurements indicated a gradual decrease in the localization of 45Ca within the implant area over time. The amounts of 45Ca found in the blood and excretions of the rats also reduced as time progressed, with only traces of 45Ca observed in the liver. From their findings, the researchers concluded that the released nanoparticles are eliminated from the body through the natural cleaning system. The possibility of nanoparticle accumulation in vital organs and potential biological risks appeared to be highly improbable based on their observations and results.

Roy et al.[92] hydroxyapatite (HA) nanocrystals measuring 200 nm in size were prepared and utilized as coatings on commercially pure titanium through the plasma spray technique. Both in vitro and in vivo biological responses were evaluated. The researchers conducted cytotoxicity tests on human fetal osteoblast cells to assess the impact of HA coatings, and in vivo studies were performed using rats. The results revealed that the fetal osteoblast cells demonstrated confluence on HA coatings, with spherical granules evident on the cell surfaces, implying the occurrence of mineralization. Also, pure titanium surfaces did not exhibit cell coverage or extracellular matrix formation. Moreover, the implantation study in rats exhibited osteoid formation on the HA-coated implant surfaces, suggesting early implant-tissue integration in vivo. These findings suggest that HA nanocrystal coatings play a significant role in promoting cell attachment, mineralization, and favorable implant-tissue interactions in both in vitro and in vivo environments.

Additive manufacturing: shaping the future of dental implants

Conventional computer numerical control machining faces significant challenges in producing dental implants that accurately replicate the intricate geometries of natural roots due to irregularly curved surfaces and complex 3D structures. An exciting alternative in this context is additive manufacturing (AM), also known as 3D printing, which possesses the unique ability to directly fabricate nearly any desired implant geometry without requiring expensive molds or tooling as presented in Figure 10. Consequently, AM is now widely regarded as the future of custom-made implants and has become a central focus in pioneering research within the dental implant domain.[93] The history of using 3D printing for dental implants dates back to the early 2000s when researchers and dental professionals first began exploring its potential in revolutionizing implant manufacturing with high precision.[94] A diverse range of 3D printing techniques are readily accessible in the market. The choice of selecting an appropriate 3D printing technique is vital and relies on the specific application in implants. The diverse nature of implant requirements necessitates careful consideration of the unique characteristics and capabilities offered by various 3D printing methods. Factors such as implant design complexity, material compatibility, resolution, and

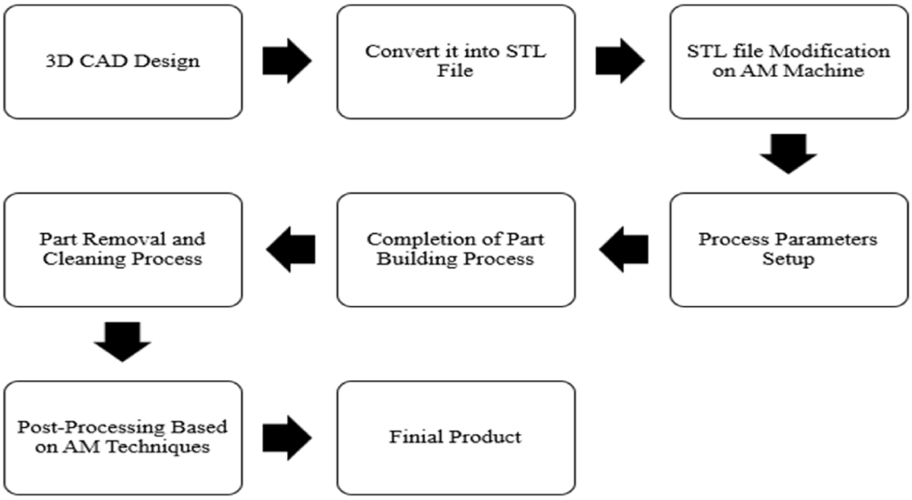


Figure 10: Steps involved in additive manufacturing processes.

production efficiency play a significant role in determining the most suitable printing technology for a particular implant application. Taking these aspects into account ensures the optimal selection of a 3D printing method to fulfill the specific needs and objectives of implant fabrication. In a study, the development of an artificial ovary was studied using extrusion-based 3D bioprinting. However, they reported that the viability of cells was lower in extrusion-based 3D culture when compared to commercial cell lines suggested that extrusion-based culture fabrication is not suitable for the development of the artificial ovary. Alternatively, the gelatin-methacryloyl-based 3D printing system provided the necessary environment for the growth of ovarian follicles in the scaffold, and thus it could be used as an alternative strategy for follicular growth and used for the treatment of female reproductive conditions.[95]

The timeline traces the development of printing techniques from their inception to the current state-of-the-art in Additive Manufacturing (AM) shown in the Figure 11. While automated processes dealing with cells, peptides, and biomaterials have been in existence for almost half a century, the initial attempts to manufacture biological constructs with living cells were reported less than a decade ago. The pioneering work in this field was conducted in the Boland laboratory, where they utilized a basic home-office desktop printer with minor modifications to deposit cells and proteins.[96] Over time, inkjet printing has been extensively studied and developed into a well-understood process capable of precisely patterning viable cells and biomaterials.[97] Several AM techniques have been developed or modified to include cells in the fabrication process, among which bio-laser printing,[98,99] stereolithography[100−103] and robotic dispensing (see Figure 12).[104−111]

AM technique utilizes data obtained from computed tomography or magnetic resonance imaging to design implants tailored to the patient's unique anatomy.[114] By adding material layer by layer, complex implant structures can be produced without the need for specific molds, reducing

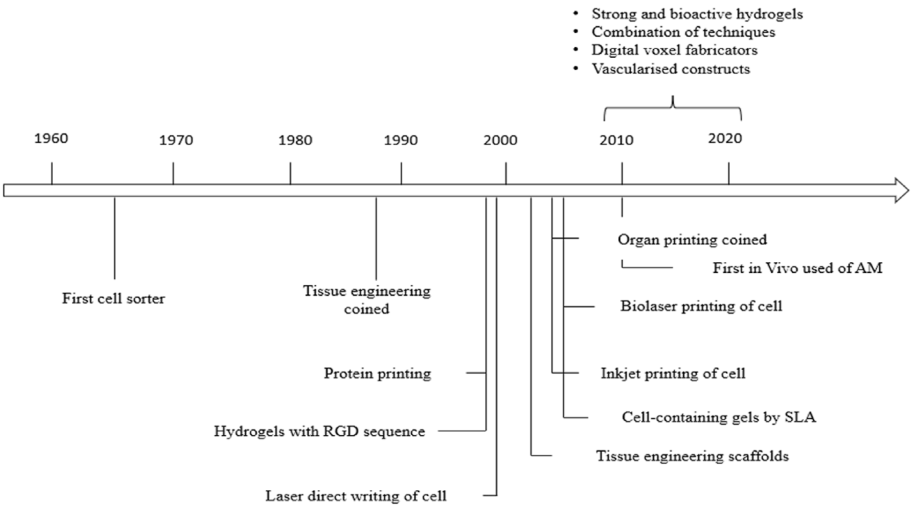
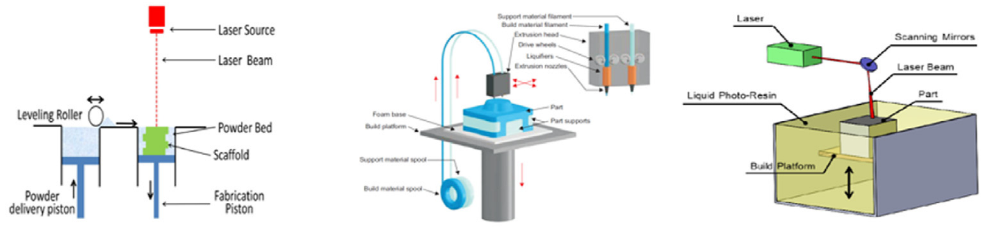


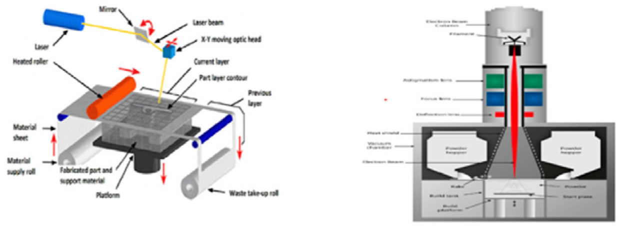
Figure 11: History of additive manufacturing and its application in tissue engineering; the introduction of technologies and major scientific findings.[112]



Selective laser sintering

Fused deposition modelling

Stereolithography



Laminated object manufacturing

Electron Beam Melting

Figure 12: Different types of additive manufacturing – Selective laser sintering, Fused deposition modelling, Stereolithography, Laminated object manufacturing, Electron beam melting.[113]

both material and time wastage. Moreover, the flexibility of additive manufacturing enables the fabrication of implants in various geometries, making it an economical and efficient choice in the field of dental implantology.[115] Below figure represents the different steps involved in additive manufacturing processes.

Interestingly, in comparison with traditional pharmaceutical technologies, 3D printing technology effectively regulated the dose of tablets according to the patient's needs by modifying the size or filling rate and helping in preparing individualized medicine.[116] Recently, orally disintegrating tablets printed by 3D printing technology are receiving a lot of attention due to the increased porosity and faster disintegration rate of the formulation.[117] Khaled et al.[118] stated the effective usage of printing technology in 3D to develop a "Polypill" consisting of 5 different active ingredients with effective personalized drug release behavior to achieve a desired therapeutic effect and improve patient survival.

Bio-tribocorrosion aspect of dental implants

The tribocorrosion is a peculiar phenomenon involving the synergistic effect[119] of mechanical wear, in all its forms such as adhesive, abrasive, fatigue, and so on coupled with the corrosive environment. Nowadays, various industrial fields (Figure 13) are subjected to tribocorrosive material loss, from industries to transportation, but also nanotechnologies, and above all, medicine and in particular implantology.[120] In that case, the term tribocorrosion is better replaced by *biotribocorrosion* since that the specific subject is the biology.[121,122] Dental, hip, and knee prostheses are clear examples of tools that undergo tribocorrosion phenomenon.[123–125]

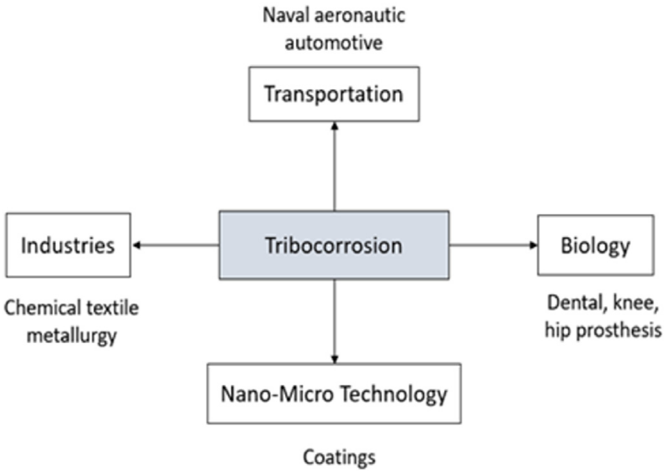


Figure 13: Application fields of tribocorrosion.

Bio-tribocorrosion represents a multidisciplinary field (Figure 14), of scientific exploration, garnering considerable attention for its clinical significance in the both oral and orthopedic field.[126] The human body poses a challenging environment for biomaterials, as it subjects them to various forms of degradation, including mechanical, chemical, biochemical, and microbiological processes.[127] In this context, bio-tribocorrosion studies offer invaluable insights into the irreversible degradation mechanisms that biomedical devices undergo by analyzing the combined effects of wear and corrosion.[128] Through a comprehensive understanding of wear–corrosion interactions, bio-tribocorrosion investigations provide critical information on the factors influencing implant performance within biological systems. Such knowledge plays a pivotal role in enhancing the design and durability of biomedical implants, ultimately propelling the field of implantology forward and yielding improved outcomes for patients.

Within the oral environment, titanium (Ti)-based implants and prostheses are the best choice for dental replacement, boasting high long-term success rates.[129] However, it is crucial to acknowledge that the tribocorrosion process can lead to implant degradation, which has been shown to influence the overall success of dental implants.[130,131] This degradation is manifested through the generation of wear cracks in the Ti-based materials, as well as the release of particles and ions. Consequently, these degradation products may evoke unfavorable biological responses, including an increase in peri-implant infection and progressive bone loss. Such adverse effects warrant meticulous attention and study to ensure long-term efficacy and durability of dental implants in oral rehabilitation.[132]

The tribolayer of metal-based implants often experiences damage due to tribocorrosion phenomena, both during implantation and throughout its lifetime in service. To begin with, material loss can take place during implantation due to friction forces acting on implants exposed to body fluids.[133] The application of insertion torque, loading, and implant replacement results in friction at the bone/implant interface, potentially leading to the release of metallic wear debris and causing alterations to the surface and geometry of the implants.[134] During mastication, the natural cyclic loads (ranging from 250 to 450 N) exerted on dental implants can create micromovements, leading to the formation of micro-gaps between the implant-abutment or abutment-prosthetic crown interfaces.[135] As a consequence of these micromovements, metal wear particles and ions may be released from the implant materials. The presence of these micro-gaps further enhances the contact between saliva, oral biofilm, and the implant surfaces, thereby exacerbating the corrosive process.[136] In addition to these factors, various characteristics of implant systems, such as the choice of structural materials, connection design, and surface treatments, also play a significant role in influencing the extent of tribocorrosion damages associated with dental implants.[137]

From a tribological perspective, the oral environment poses a highly complex and aggressive condition for metallic implants. The combined presence of saliva and microorganisms exerts dual effects on dental implants, playing a crucial role in the occurrence of bio-tribocorrosion phenomena.[138] Within the oral environment, the techniques employed for biofilm control and decontamination of implant surfaces, such as mechanical, chemical, and simultaneous procedures, can also be contributing factors that enhance the surface tribocorrosion.[139]

Literature tribocorrosive outcomes of traditional manufacturing of dental implants

In this framework, several scientists tried to buffer tribocorrosive effects in terms of material choice and coating, adopted treatment[140] and so on.[141] For instance, Toptan et al.[142] found out that the porosity of titanium samples acts against the corrosion during sliding thanks to the hard oxide layer formed on the surface and to insertion of wear debris into the pores avoiding the third-body abrasion. Alves et al.[143] investigated the effect of the plasma electrolytic oxidation method in comparison with the bare titanium, finding an increase in anti-wear performances as a result of anodic film growth. Oliveira et al.[144] noted that the concentration of calcium acetate modified the microstructure of the protective oxide layer providing better anti-tribocorrosive behavior. The positive tribological function made by calcium was confirmed also by Marques et al.[145] because of the formation of a hard and porous rutile crystalline structure, especially when nanoparticles of silver

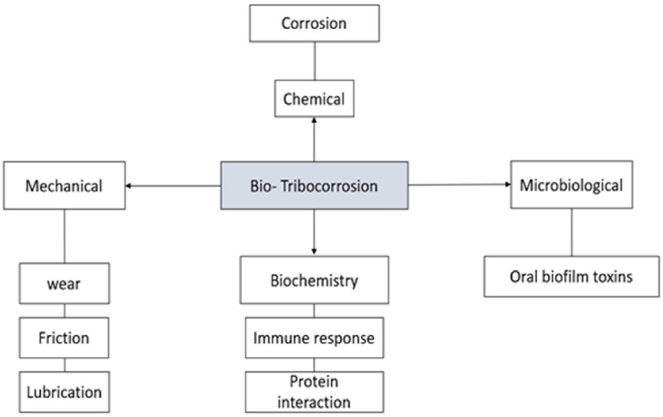


Figure 14: Concept and definition of Tribocorrosion.

are added.[128] Zhao et al.[146] analyzed the impact of NTNTs-TiN coating on Titanium Grade V alloy immersed in a solution including simulated body fluid, noting a relevant reduction of tribocorrosive wear as well as a decrease of friction coefficient due to the formation of lubrication film enriched of elements like calcium, magnesium, and potassium. In addition, Ribeiro et al.[147] found that a calcium-rich layer, deposited on bulk titanium, facilitated the osteoblast adhesion and regulated the inflammatory responses and bone microstructure, thanks to a great production of IFN-γ cytokine. Biologically speaking, even the bacteria issue, as said before, should be taken into consideration. Indeed, He et al.[148] demonstrated that by applying a ceramic layer of Cu_xO/TiO_2 on titanium alloy, not only the wear resistance increases but also the antibacterial activity, strictly correlated with the content of copper. Cordeiro et al.,[149] instead, investigated the Ti–Zr alloy behavior in comparison with the commercial pure (CP) one: the former presented lower roughness and Young's modulus but higher hardness and corrosion resistance with respect to the latter.

Overall, it is almost obvious that CP titanium has worse mechanical and tribological properties than specific titanium alloys. Nevertheless, there is no still clinical evidence for a complete and permanent substitution in favor of the worked alloys,[150] reason why more in vivo experiments are required. However, as it easily is notable, the majority of the studies conducted have involved titanium as implant material, which is the most common kind among orthopedics and dental implants.[151] This does not entail that is the best and unique alternative. Indeed, it has some drawbacks such as a Young's modulus much higher than human cortical bone, which is not perfectly mechanically balanced with the bone. Consequently, it should be useful to consider introducing elements such as zirconium to reduce the modulus, as done by Kuroda et al.[152] Moreover, it, as well as vanadium or aluminum, is toxic to human cells. The ions, in particular, can attack both the bone-implant interface and the blood circulation causing inflammations and severe biological reactions.[153] In this regard, Silva et al.[154] discussed the effect of gold as abutment framework in relation to ion release, discovering that it reduced the concentration of titanium spikes. For these reasons, valid alternatives have been proposed for example by Xu et al.[155] for the use of niobium not only for good mechanical performance but also from a biological and clinical point of view. In fact, it can promote cellular attachment, and osteogenic processes and it is not clinically dangerous.

On the whole, the tribocorrosive research, despite the massive improvements, has still several questions and doubts to answer.

Bio-tribocorrosion study of dental implant made by additive manufacturing

The selective laser melting (SLM) method is increasingly utilized for producing Ti6Al4V due to its ability to create alloys with comparable or superior mechanical properties respect to conventional techniques.[156] During the SLM process, a high-intensity laser beam selectively scans across a powder bed, melting the irradiated particles, and allowing them to solidify into a solid layer. Successive layers of powder are deposited on top of each previously formed solid layer, and this cycle continues until the entire part is fully fabricated.[157] When considering design freedom, manufacturing flexibility, specific requirements for complex designs, strict quality control, and low to medium-volume production, SLM emerges as a significantly superior choice.[158–160] Attar et al.[161] investigation of wear properties reveals that SLM-processed samples exhibit enhanced wear resistance in comparison to their cast counterparts. Despite this difference, both the SLM-processed and cast CP-Ti samples display similar wear mechanisms. These promising findings suggest that the SLM process is capable of producing CP-Ti parts with complex shapes and superior wear properties when compared to the casting technique.

Toh et al.[162] conducted a study to examine the dry sliding wear behavior of Ti6Al4V alloy produced through electron beam melting (EBM), which is a technique akin to SLM. The investigation involved testing the alloy against a 6 mm diameter 100Cr6 steel ball under a 1 N normal load and a sliding speed of 2 cm/s for a total of 50,000 cycles and comparing it with the same alloy made by casting. Despite observing similar wear characteristics in samples produced by the two different techniques, the EBM-produced samples demonstrated superior wear resistance. Amaya-Vazquez et al.[163] investigated the impact of laser remelting on the electrochemical behavior of Ti6Al4V in a 3.5 wt.% NaCl solution. Their findings revealed that the presence of a martensitic microstructure in laser-remelted Ti6Al4V samples led to enhance corrosion resistance. Toptan et al.[164] examined the corrosion and tribocorrosion characteristics of SLM-produced Ti6Al4V alloy and compared them with the alloy's counterparts produced through Hot Pressing and commercial methods. The results indicated that the SLM processing route had an impact on the electrochemical response of the SLM-produced alloy. Specifically, it led to a comparatively lower formation of the passive film due to the reduction in β phase and the formation of α' phase. However, the tribocorrosion outcomes showed no statistically significant differences between the processing routes in terms of total volume loss or volume loss influenced by mechanical wear and wear-accelerated corrosion. Vaithilingam et al.[165] investigation into the surface chemistry of SLM-produced Ti6Al4V following remelting and skin scanning processes. They found significant differences compared to the conventional forged alloy. Notably, the variations in oxide film thickness and the higher Al concentration on the surface were identified as potential factors influencing the electrochemical response. The use of laser, and in particular the selective laser melted technique, was adopted also by Hamza et al.,[166] by comparing the corrosion behavior of a Ti6Al4V treated with this technique and a conventional manufactured one, in different solutions. The results showed a preference for the former in solutions with $pH > 6$ thanks to higher amount of β-phase and of vanadium which promoted the formation of protective oxide layer. On the contrary, the latter performed better for $pH < 6$ thanks to higher amount of α-phase and the presence of aluminum which enhanced the corrosion resistance. However, the selective laser method should be coupled with acid etching as confirmed by de Souza Soares et al.[167] because of not fused particles which decreased the barrier to corrosion. Hence the acid results crucial for removing these particles as much as for obtaining a surface with appropriate roughness. Moreover, Atapek et al.[168] studied the tribocorrosion behavior of both cast and selective laser melted CoCr alloy, discovering that the second one were more resistant to tribocorrosive wear because of the higher hardness and more stable oxide protective layer formed on the surface. Vilenha et al.[169] weighed Ti6Al4V fabricated by selective laser melting against one realized conventionally. If the friction coefficient and the wear rate coefficient were almost similar, the current density was found lower for the former. The same comparison was considered by de Jesus et al.[170] during a fatigue test including artificial saliva environment. The calculated wear rate were of the same order of magnitude certifying thus the feasibility of additive manufacturing dental implants. Buciumeanu et al.[171] instead, explored the diverse behavior of NiTi and Titanium Grade V alloys, both realized by laser beam directed energy deposition technique. The first showed worse corrosion resistance, with no sliding, respect to the other one, but showed an opposite behavior in terms of volume loss when the tribocorrosion test was carried out. Consequently, it exhibited a better response against the mechanical and corrosion wear. In addition, the diversity of outcomes highlights the importance of performing the tribocorrosion test for a rigorous characterization of material. Similar to titanium samples, also a CoCrMoW alloy, worked via Laser Metal Fusion, was compared with wrought LC CoCrMo in Mace and Gilbert[172] study. Very close anti-wear responses between them were found, confirming again the additive manufacturing medical tools as valid alternative. Zhang et al.[173] stated that a 3D zirconia sample not only reached a satisfactory level of mechanical resistance, comparable to the tools realized by subtractive manufacturing methods, but also an enhancement of cellular activity. In fact, the peculiar surface patterns with directional pores promoted the osteoblast response whereas the dense core the long-term mechanical resistance. The relevance of porosity was discussed, for titanium scaffolds, by Hou et al.,[174] for different microstructures regarding the stress—strain regime which was acceptable for dental applications and osteogenesis properties. Besides, larger pores, which promote the growth of the bone, are more subjected to corrosion as demonstrated by Morris et al.[175] Hence a trade-off between these two aspects drives to the optimal configuration.

Before proceeding with additive manufacturing (AM), it is crucial to engage in thorough discussions and simulations of the research. This step holds paramount importance as it lays the foundation for obtaining optimum results in the fabrication process. Through meticulous simulations, researchers can explore various design iterations, assess potential challenges, and analyze the performance of the intended product. By simulating the proposed AM process, engineers and designers can identify and address potential issues, optimize the geometry and material parameters, and enhance overall efficiency. Additionally, simulated research aids in minimizing errors, reducing material waste, and avoiding costly manufacturing setbacks. It provides a cost-effective and time-efficient means to fine-tune the design and ensure that the final product meets the desired specifications. By scrutinizing and validating the simulation results, one can gain valuable insights that lead to informed decisions during the actual additive manufacturing process, ultimately resulting in the achievement of superior and optimized outcomes.

Overall, it is almost obvious that further tribocorrosive trials are required to confirm these assumptions. Moreover, despite the great potential of this technology, some drawbacks, unfortunately, exist such as the impossibility of creating nanoscale or bioactive surfaces without a subsequent treatment[176] as well as the absence of standard protocols[177] and of a biological and medical long-term response, requiring more and more clinical investigations.[178]

Conclusions

The implants possess complex geometries and the mechanical, tribological, corrosion, and biological aspects need to be studied in detail. Conventional manufacturing processes face difficulties in developing complex and intricate shapes. The literature revealed that studies have focused on developing new implants by 3D printing and comparing the properties with conventionally manufactured implants. The properties as reported by researchers are promising, however, the area has not been explored for a wide range of materials and properties as required from an oral environment point of view.

The absence of clinical and long-term tribocorrosive analyses, since their undeniable relevance, underlines the most critical limitations of this work. Hence, although dental implants realized by additive manufacturing are a potential alternative to the traditional ones, the results should be treated with caution. Moreover, the development of new implant materials with specific coatings[179] or functionally grading can be explored with 3D printing as future development as much as conducting further experiments by varying the tribological and chemical conditions like contact pressure, motion regime, kind of solution and so on. Indeed, the reliability of these tools can be proved only by testing it in different scenarios reflecting specific human daily activities and clinical conditions such as smoking issue which is strictly correlated with implant failure.[180] Analogously, nanotechnology and nanoengineering could outline an interesting prospect especially for the concept of osseointegration.[181] In conclusion, 3D printing if exploited in the area of dental implants can help to develop implants with intricate shapes and with tailored properties without jeopardizing the biocompatibility which results crucial for the longevity of the medical tools.

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Conflict of interest

The authors have no conflict of interest to declare.

Ethical approval

There is no ethical issue.

Authors contributions

Authors testify that all persons designated as authors qualify for authorship and have checked the article for plagiarism. If plagiarism is detected, all authors will be held equally responsible and will bear the resulting sanctions imposed by the journal thereafter. All authors should meet all four of the following criteria: Substantial contributions to the conception or design of the work; or the acquisition, analysis, or interpretation of data for the work; Drafting the work or revising it critically for important intellectual content; Final approval of the version to be published; Agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. MIUH, MDS, KS, AR, ARi and SM conceived and designed the study, conducted research, provided research materials, and collected and organized data. MIUH and ARi analyzed and interpreted data. MDS and KS wrote initial and final draft of article, and provided logistic support. All authors have critically reviewed and approved the final draft and are responsible for the content and similarity index of the manuscript.

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