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3D-printed silicon nitride ceramic implants for clinical applications: the state of the art and prospects

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Si_3N_4 ceramic has received great attention because of its sound biological performances, which make it an attractive ceramic implant material in healthcare, particularly in orthopedic surgery. With the advancement of 3D printing technology, Si_3N_4 ceramics can now be fabricated into customized implants with precise anatomical shapes, sizes, and microstructures, catering to the individual needs of patients. We, therefore, conducted a comprehensive review of how 3D printing enables complex-shaped Si_3N_4 ceramic implants for clinical applications. Firstly, commonly used 3D printing technologies are introduced. Then, the state of the art of the 3D-printed Si_3N_4 ceramic implants are summarized. Finally, we forward the prospects towards the 3D printing of Si_3N_4 ceramic implants, including high mechanical properties, composites, drug loading, and economics and low cost. We hope that this review will provide a thorough examination and helpful guidance to related scientists, clinicians, and dentists in this field.

1. Introduction

Silicon nitride (Si_3N_4) is a non-oxide ceramic extensively used in system parts subjected to high stress and/or high temperatures, owing to its outstanding properties such as low density, high strength, high fracture toughness, high hardness, excellent wear resistance and creep behavior, and excellent resistance at elevated temperatures.[1–3] Recently, in addition to its excellent physicochemical and mechanical properties, Si_3N_4 ceramic has received great attention because of its sound biological performances, which make it an attractive implant material in healthcare, particularly in orthopedic surgery.[4–6] Si_3N_4 ceramic is used clinically in developing bearings in total hip and knee joint replacement, spinal space fusion devices, and so on (as shown in Fig. 1).[7] Some transnational corporations, such as CeramTec Industrial, SINTX Technologies, and so on, have achieved great success in the field of Si_3N_4 ceramic hip and knee joint replacement. In addition, Si_3N_4 ceramic implants have also been reported to be used in dental clinics. According to some market reports, Si_3N_4 ceramic implants will increase at a compound annual growth rate of over 17.5% from 2024 to 2031, perhaps reaching over USD 10 billion. Table 1 lists the possible clinical applications of 3D-printed Si_3N_4 ceramic implants, including these dental implants, orthopedic implants, and other customized implants, which show great potential and value.

As is known, ceramic implants are always complex in geometry, sometimes even with porous, gradient, and other shape features. It is a difficult task to manufacture complex-shaped Si_3N_4 ceramic components. At present, 3D complex-shaped Si_3N_4 ceramic components are commonly produced through two approaches: sintering and machining,[8,9] and near-net forming and sintering.[10,11] Fig. 1 clearly shows the traditionally prepared Si_3N_4 ceramic components for all kinds of possible clinical applications. However, for the sintering and machining approach, bulk Si_3N_4 ceramic is firstly fabricated by various sintering technologies, such as pressureless sintering, hot pressing, and so on. Complex-shaped Si_3N_4 components are subsequently obtained through grinding, turning, and other machining methods. Inevitable defects and damages exist owing to the deadly brittleness and hardness of ceramic during machining, which greatly deteriorate its properties and life.[12–14] In addition, expensive diamond or superalloy machining tools are needed for machining, which greatly increases the costs.[9,12] For the near-net forming and sintering approach, a complex-shaped Si_3N_4 green body is usually prepared *via* near-net colloidal processing technologies, such as slip casting, tape casting, injection molding, gel casting, and so on.[11,15,16] After that, the Si_3N_4 component is subsequently obtained by using pressureless sintering. However, molds are usually needed, which increase the production cycles and cost. Moreover, extremely complex-shaped Si_3N_4 components may contain internal holes or internal surfaces, which are very difficult to achieve. In one word, both these sintering and machining and near-net forming and sintering approaches cannot meet the manufacturing requirement of 3D complex-shaped Si_3N_4 ceramic components.

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Fig. 1 Clinical applications of Si_3N_4 ceramic components (SINTX Technologies).[7]

Additive manufacturing (AM), also known as 3D printing, is promising for net- and near-net shaping of Si_3N_4 ceramic components.[17,18] Recently, many studies have shown that geometrically complex SiOC,[19] oxide,[20] hydroxyapatite,[21] SiC,[22] and ceramic composite[23] components are readily fabricated by 3D printing. Fig. 2 shows published paper numbers with the topics "3D printing" and "Si_3N_4" to papers with the topic "Si_3N_4" (Web of Science database from 2014.01 to 2024.11). It is found that, in the past 10 years, the 3D printing of Si_3N_4 ceramic has drawn increasing attention and has been subjected to intensive research. Among these studies, an increasing number of novel 3D-printed Si_3N_4 ceramic implants have been investigated and used in the biomedical field. However, on the one hand, the state of the art of the 3D printing of Si_3N_4 ceramic lacks a comprehensive review and summary. On the other hand, there are still many challenges and issues regarding the 3D printing of Si_3N_4 ceramic implants and their biomedical clinic applications, which need to be systematically discussed.

Therefore, this paper aims to systematically review the recent state of the art to assess the prospects for novel 3D-printed Si_3N_4 ceramic implants for biomedical applications. The authors hope to provide a deep review and helpful guidance for the related scientists, clinicians, and dentists in this field.

2. 3D-printed Si_3N_4 ceramics

According to the ISO/ASTM 52900:2015—Additive manufacturing,[24] 3D printing technologies can be divided into seven categories: vat photopolymerization (VPP), material extrusion (MEX), material jetting (MJ), binder jetting (BJ), powder bed fusion (PBF), direct energy deposition (DED), and sheet lamination (SL). In this paper, commonly used 3D printing technologies for Si_3N_4 ceramics that were published recently are summarized as follows.

2.1 Vat photopolymerization (VPP) 3D-printed Si_3N_4 ceramics

Vat photopolymerization (VPP) 3D printing process is a technique in which photosensitive ceramic slurries are exposed to

Table 1 Possible clinical applications of 3D-printed Si_3N_4 ceramic implants

Implants		Description
Dental application	Post-core crown	3D-printed Si_3N_4 ceramic implants are promising new implants for restoring large-area dental defects, which can serve as the post portion of a post-and-core crown, providing stable retention force
	Bone screws, surgical plates, screw shafts, and other devices	3D-printed Si_3N_4 ceramic implants can be used as bone screws, surgical plates, screw shafts, and other devices. Si_3N_4 ceramic can effectively integrate with surrounding tissues and promote new bone formation
Orthopedic application	Hip and knee replacements	3D-printed Si_3N_4 ceramic implants can be used as components for hip and knee replacements. Si_3N_4 ceramic is an ideal choice for replacing traditional Al_2O_3 ceramics
	Cervical spacers and spinal fusion cages	3D-printed Si_3N_4 ceramic implants can be used as cervical spacers and spinal fusion cages. Especially in spinal surgery, porous Si_3N_4 ceramic scaffolds for intervertebral body fusion have achieved remarkable clinical effects
Other clinical applications		3D-printed Si_3N_4 ceramic implants with precise anatomical shapes, sizes, and microstructures can be applied for other clinical applications

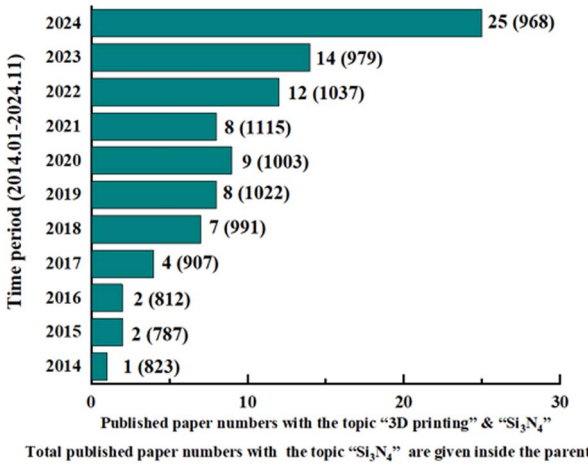

Fig. 2 Published paper numbers with the topics "3D printing" and "Si_3N_4" to papers with the topic "Si_3N_4" (Web of Science database from 2014.01 to 2024.11).

radiation/light in a controlled manner to obtain polymerized material layers, as shown in Fig. 3a. Subsequent layers combine to form a 3D ceramic green object. After that, debinding and sintering are further conducted to obtain the final ceramic parts. Usually, VPP 3D printing processes can further be classified into stereolithography (SLA, as shown in Fig. 3a(i)),[25] digital light processing (DLP, as shown in Fig. 3a(ii)),[25] two-photon polymerization (2PP, not shown here),[31] volumetric 3D printing,[32] and so on. Recently, Si_3N_4 ceramics have been widely reported to be fabricated by VPP 3D printing. Schwarzer-Fischer *et al.* successfully prepared Si_3N_4 ceramic and its complex structures, such as discs and triple periodic minimal surfaces (TPMS),[33] as shown in Fig. 4a. Zhou *et al.* also fabricated Si_3N_4 ceramic by VPP 3D printing. Combined with following air pressure liquid-phase sintering, the as-obtained Si_3N_4 ceramic had a relatively high strength of 382.67 MPa and a density of 2.95 g cm^{-3}.[34] They further investigated the effect of thermo-setting resin coating modification on the properties of Si_3N_4 ceramics, as shown in Fig. 4b.

2.2 Materials extrusion (MEX) 3D-printed Si_3N_4 ceramics

Materials extrusion (MEX) 3D printing of ceramics requires continual feeding of material within a moving nozzle. This process enables simple extrusion *via* the nozzle, molding layers along a preset path. After finishing a layer, the build platform or the extrusion head moves up or down, allowing for the deposition and adhesion of another material layer to the previous one. After ceramic green parts are obtained, debinding and

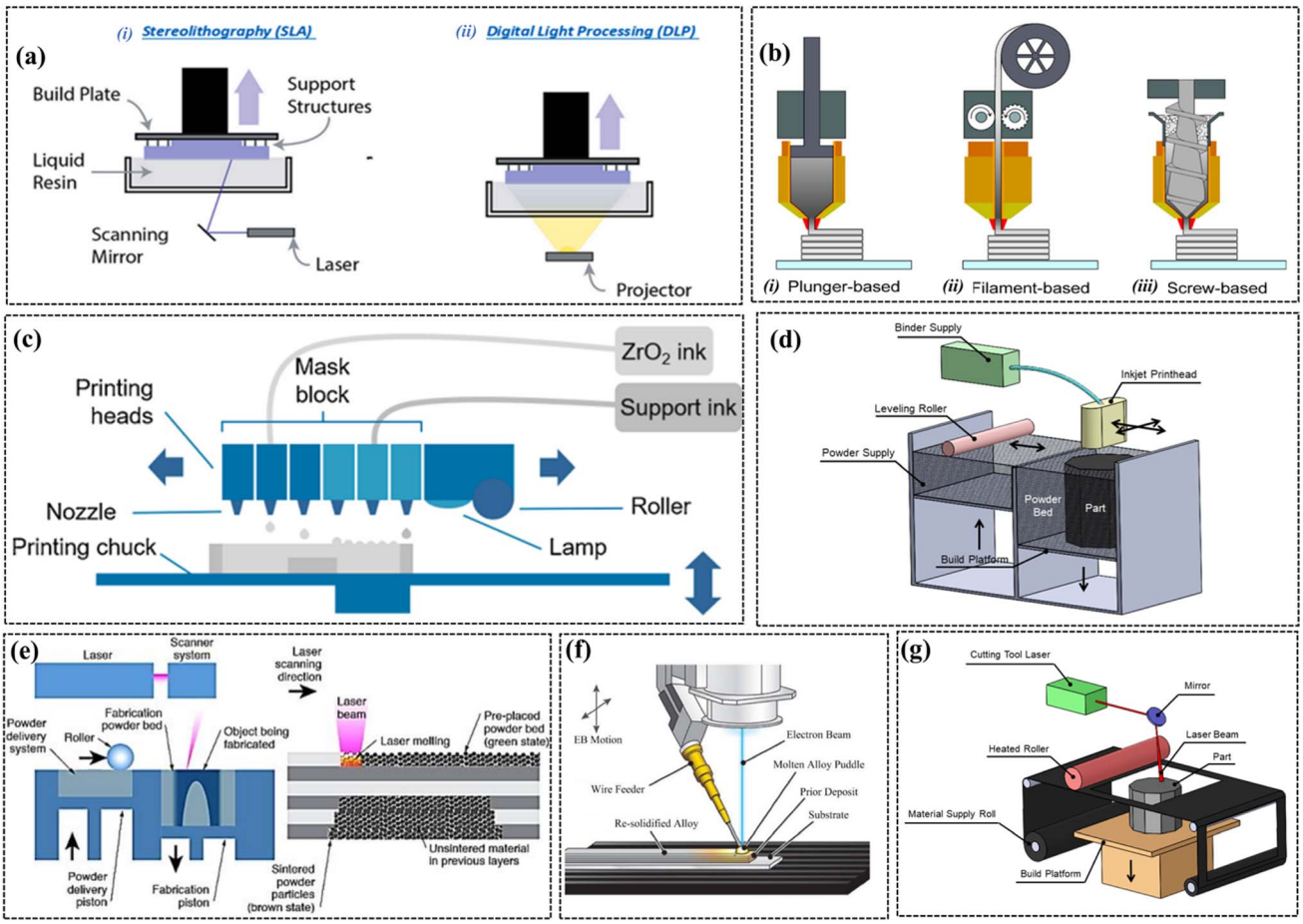

Fig. 3 3D printing technologies: (a) VPP,[25] (b) MEX,[26] (c) MJ,[27] (d) BJ,[28] (e) PBF,[29] (f) DED,[30] and (g) SL.[28]

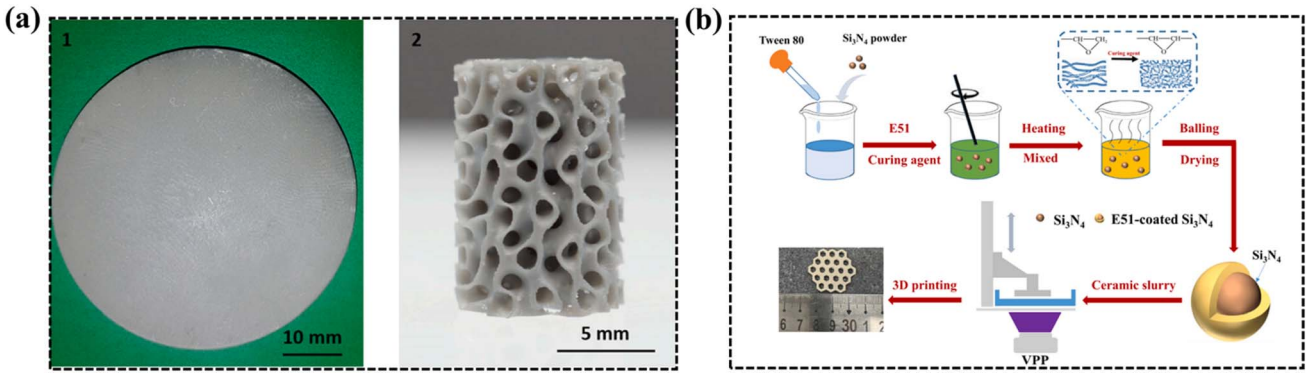

Fig. 4 VPP 3D printing of Si_3N_4 ceramic: (a) discs and TPMS[33] and (b) thermosetting resin coating modification during 3D printing.[34]

sintering are subsequently conducted. Usually, MEX 3D printing of ceramics can usually be classified into three types (as shown in Fig. 3b): filament-based, plunger-based, and screw-based.[26] Clarkson *et al.* used a UV-assisted direct ink writing (DIW), which is a type of MEX 3D printing, to prepare Si_3N_4/SiC from preceramic polymer suspensions.[35] After post-pyrolysis, hexagonal arrays, lattice or log pile structures, and twisted vases were obtained (as shown in Fig. 5a). Jiang *et al.* also prepared Si_2N_2O–Si_3N_4 ceramics *via* DIW and following low-temperature sintering.[36] Spina *et al.* also obtained some Si_3N_4 ceramic parts, including a rectangular bar, turbine rotor, gear, and swirl fan,[26] by MEX 3D printing, as shown in Fig. 5b.

2.3 Material jetting (MJ) 3D-printed Si_3N_4 ceramics

Material jetting (MJ), also known as direct inkjet printing, is shown in Fig. 3c. This technique makes use of an organic binder to shape the green body component and requires postprocessing such as debinding and sintering to obtain the final densified object.[27] Willems *et al.* attempted to prepare 3Y-TZP ceramic by using MJ 3D printing, with an as-printed green density of 58% and nearly fully sintered density of 6.03 g cm^{-3} (99.7% relative density).[27] Complex-shaped ceramic components were successfully achieved by MJ 3D printing, as shown in Fig. 6; however, there has been no report on the MJ 3D printing of Si_3N_4 ceramic until now.

2.4 Binder jetting (BJ) 3D-printed Si_3N_4 ceramics

Strictly speaking, binder jetting (BJ) 3D printing technology is a type of MJ. Fig. 3d shows the BJ 3D printing of ceramic. The roller spreads the ceramic powder of the powder tank under the nozzle. After that, the nozzle jets the binder to the predetermined areas. Then, the forming platform descends to a certain height, so back and forth. Finally, a 3D ceramic green body is formed on the forming platform.[28] Rabinskiy *et al.* fabricated porous Si_3N_4 ceramic using BJ 3D printing technology.[37] Sintered Si_3N_4 ceramic had a porosity up to 70%. This work provided some ideas for the 3D printing of dense or porous Si_3N_4 ceramic components.

2.5 Powder bed fusion (PBF) 3D-printed Si_3N_4 ceramics

As shown in Fig. 3e, powder bed fusion (PBF) methods, such as selective laser sintering (SLS), can be employed for 3D printing of ceramics. Normally, ceramic powders are laid on the forming platform. The heat source (laser, plasma, *etc.*) moves according to the setting path to irradiate the ceramic powders. The temperature of the irradiated ceramic powders hence rises sharply to a temperature lower than the melting point, and sintering occurs. Then, the ceramic powders are spread by a doctor blade and sintered layer by layer, and finally form a 3D complex-shaped ceramic component.[29] Minasyan *et al.* fabricated Si_3N_4-based complex geometry parts by SLS.[38] They first

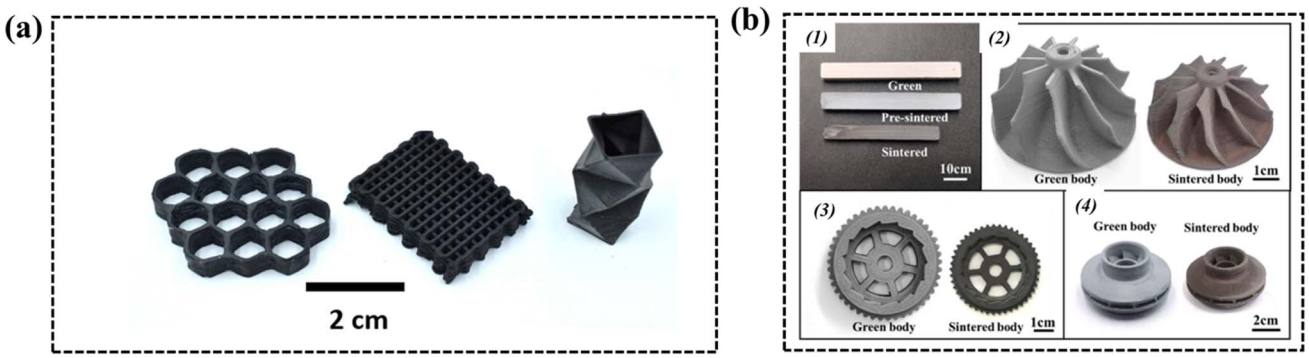

Fig. 5 MEX 3D printing of Si_3N_4 ceramic: (a) hexagonal array, lattice or log pile structure, and twisted vase;[35] (g) rectangular bar, turbine rotor, gear, and swirl fan.[26]

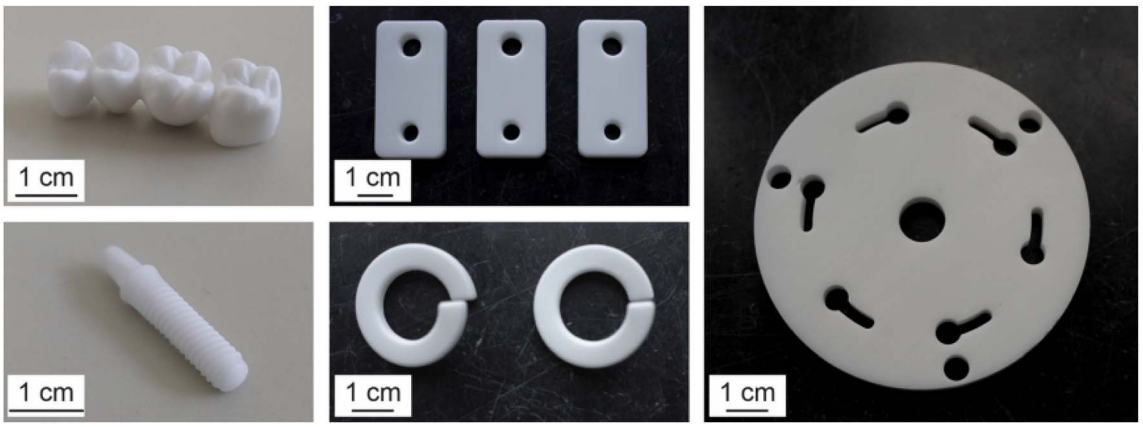

Fig. 6 MJ 3D printing of ceramic components.[27]

used SLS on silicon powder to provide the required shape, and then conducted nitridation on the as-shaped silicon parts to fabricate the Si_3N_4 component. Wang *et al.* prepared a high-strength Si_3N_4 ceramic antenna window using SLS, combined with cold isostatic pressing (CIP) after debinding before final sintering,[39] as shown in Fig. 7a. The porosity, bulk density, and bending strength of the 3D-printed Si_3N_4 ceramic were 18.7%, 3.11 g cm^{-3}, and 685 MPa, respectively. Wu *et al.* applied AlN as an inorganic binder during the SLS of porous Si_3N_4 ceramic, with a total porosity of 33.6% and a flexural strength of 23.9 MPa, respectively.[40] Finally, they prepared complex-shaped porous Si_3N_4 ceramic components, as shown in Fig. 7b.

2.6 Direct energy deposition (DED) 3D-printed Si_3N_4 ceramics

Fig. 3f shows the DED 3D printing.[30] Supply material is directed at the heat source, at the point of deposition. Without the use of hard tooling, this innovative process provides a solution to build complex parts with near-net shapes at a much faster rate than the aforementioned processes. However, there have rarely been any reports on the DED 3D printing of ceramics so far.

2.7 Sheet lamination (SL) 3D-printed Si_3N_4 ceramics

Sheet lamination (SL), also called laminated object manufacturing (LOM), is a 3D printing process in which consecutive layers of paper sheets covered by adhesive applied to one side are continuously bonded and cut with a laser to form a 3D component, as demonstrated in Fig. 3g.[28] Liu *et al.* prepared Si_3N_4 ceramic components by aqueous tape casting in combination with LOM.[41] Homogeneous green Si_3N_4 ceramic sheets consisting of 48.7 vol% ceramic particles were prepared by tape casting. Then, Si_3N_4 ceramic components with complex shapes were fabricated by layer-by-layer stacking of the green sheets and a subsequent pressureless sintering, as shown in Fig. 8.

To sum up, we summarized the characteristics and advantages/disadvantages of different 3D-printed Si_3N_4 ceramics, as listed in Table 2. Each 3D printing technology has its printing accuracy, advantages, and disadvantages. From the comparison between different 3D printing technologies for Si_3N_4 ceramics, it is found that VPP and MEX have the most notable accuracy and advantages, resulting in them being widely reported for the preparation of Si_3N_4 ceramic implants.

3. 3D-printed Si_3N_4 ceramic implants

Although Si_3N_4 ceramic has been widely manufactured by various 3D printing technologies in the past 10 years, the most common 3D-printed Si_3N_4 ceramic implants for biomedical applications are mainly obtained by VPP 3D printing and MEX 3D printing.

3.1 VPP 3D-printed Si_3N_4 implants

In 2019, Lithoz GmbH, a famous ceramic 3D printing company, fabricated dense, strong, and precise Si_3N_4 ceramic parts by a so-called "lithography-based ceramic manufacturing (LCM)" 3D printing technology, which is a type of VPP 3D printing.[42] They mixed Si_3N_4 ceramic particles, solvent, and

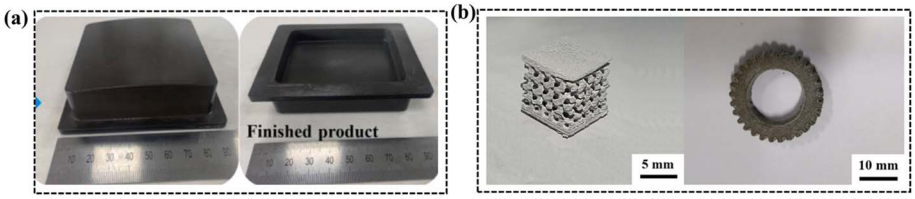

Fig. 7 PBF 3D printing of Si_3N_4 ceramic: (a) Si_3N_4 ceramic antenna window[39] and (b) complex-shaped porous Si_3N_4 ceramic components.[40]

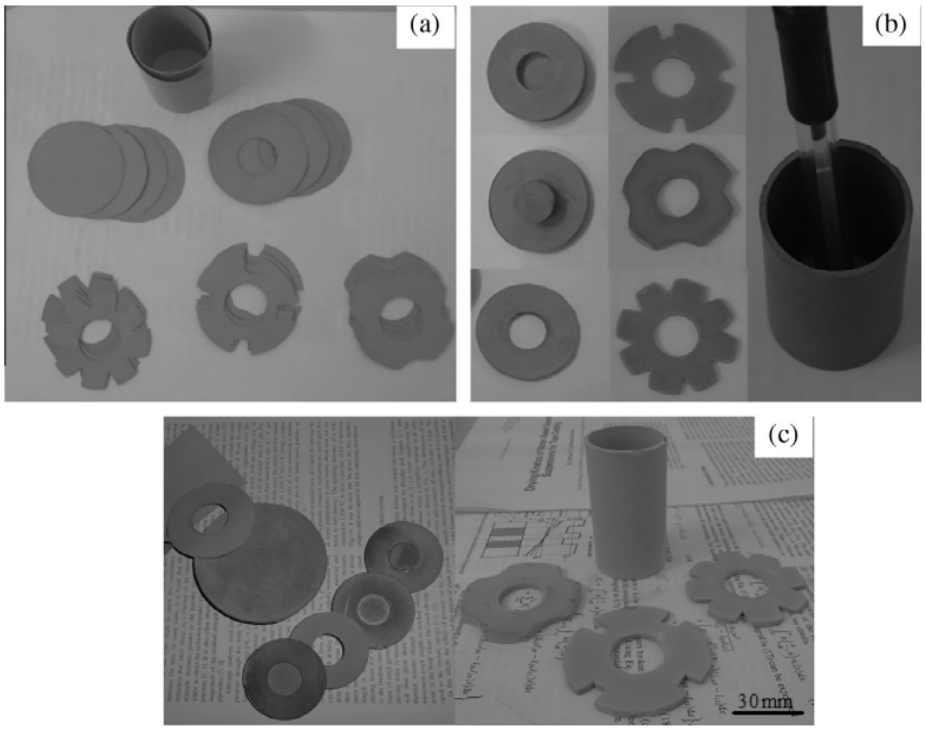

Fig. 8 SL 3D printing of Si_3N_4 ceramic: (a) green pieces, (b) green bodies, and (c) sintered components.[41]

a photopolymer network together, and then the as-prepared slurry mixture was cured under 460 nm light. Si_3N_4 green parts were 3D-printed, and Si_3N_4 final parts were successfully fabricated after debinding and sintering. The LCM 3D-printed Si_3N_4 ceramic was reported to have a high relative density (99.8%), high biaxial strength ($\sigma_f = 764$ MPa), and high hardness ($HV_{10} = 1500$). They also verified the potential biomedical implant applications, such as dental two-piece implants with M1.6 inner threads, of the LCM 3D-printed Si_3N_4 ceramic, as shown in Fig. 9a. After that, many researchers made tremendous efforts in the field of VPP 3D-printed Si_3N_4 implants and achieved great progress. In 2023, Zou *et al.* used another kind of VPP 3D printing, digital light processing (DLP), and prepared high-performance VPP 3D-printed Si_3N_4 implants for dental use.[43] They first prepared ceramic slurry from Si_3N_4 powder, photosensitive resin monomer (HDDA and TMPTA), photoinitiator (Omnirad 380), and sintering additives (yttrium oxide and alumina), with a high solid loading of 40 vol%. Si_3N_4 ceramic parts were 3D-printed, debinded, and sintered. The as-prepared Si_3N_4 ceramic has a high three-point flexural strength of 770 MPa and an excellent fracture toughness of 13.3 MPa $m^{1/2}$ (as shown in Fig. 9b). They continued to investigate the VPP 3D-printed Si_3N_4 implants by *in vitro* biological experiments and found the implants exhibited good biocompatibility. A hemolysis test, oral mucous membrane irritation test, and acute systemic toxicity test (oral route) further confirmed that the VPP 3D-printed Si_3N_4 implants did not exhibit hemolysis reaction, oral mucosal stimulation, or systemic toxicity. These findings indicated that VPP 3D-printed Si_3N_4 dental implant restorations with personalized structures had good mechanical properties and biocompatibility, which has great application potential in the future.

In addition, porous Si_3N_4 ceramic implants were also reported by VPP 3D printing, since porous ceramic structures were beneficial for the following biocompatibility and biomedical applications. In 2023, Huang *et al.* reported a porous Si_3N_4 ceramic by VPP 3D printing.[44] They added hawthorn nuclear powder as the pore former and used Al_2O_3

Table 2 Comparison between different 3D printing technologies for Si_3N_4 ceramics

3D printing	Accuracy	Advantages	Disadvantages
VPP	μm	High accuracy	Hard to burn out the resin
MEX	μm–mm	Easy forming	Low accuracy, low strength
MJ	mm	—	Low accuracy, low strength
BJ	mm	—	Low accuracy, low strength
PBF	μm–mm	—	High thermal stress, high number of defects and cracks
DED	μm–mm	—	High thermal stress, high number of defects and cracks
SL	mm	—	Hard to form ceramic sheet

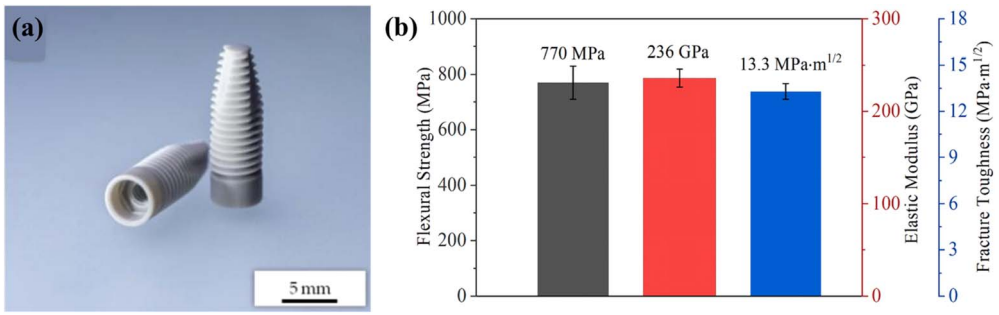

Fig. 9 (a) LCM 3D-printed Si_3N_4 ceramic dental two-piece implants;[42] (b) high-performance VPP 3D-printed Si_3N_4 implants for dental use.[43]

and Y_2O_3 as the sintering additives. The maximum porosity of the VPP 3D-printed Si_3N_4 ceramic was 58.48% (as given in Fig. 10a), and the compressive strength and Young's modulus were 79 MPa and 18 GPa, respectively. *In vitro* cytotoxicity assays were performed, and cell viability was assessed. Finally, they 3D-printed porous Si_3N_4 ceramic bone for verification (as presented in Fig. 10b and c). The VPP 3D-printed porous Si_3N_4 ceramic did not exhibit significant cytotoxicity and was capable of supporting the growth of rat bone marrow mesenchymal stem cells (rBMSC), which indicated excellent biocompatibility and potential for bone application.

3.2 MEX 3D-printed Si_3N_4 implants

In 2016, Zhao *et al.* prepared Si_3N_4 ceramic with controlled shape and architecture for biomedical application by using a so-called robocasting technology, which was a kind of materials extrusion 3D printing.[45] In their study, an aqueous paste composed of Si_3N_4 powder and sintering additives was prepared with the requisite rheology and formed into structures with different geometry and architecture by using robocasting (as given in Fig. 11a and b). Sintering and hot isostatic pressing produced an almost fully dense Si_3N_4 phase (density = 3.23 g cm^{-3}) with a fibrous microstructure. Four-point bending tests of as-fabricated dense Si_3N_4 ceramic beams showed a flexural strength of 552 MPa. The as-printed Si_3N_4 ceramic parts had a controlled surface roughness, and the average surface roughness (R_a) found by AFM was 0.75 μm (as shown in Fig. 11c). They found the Si_3N_4 parts fabricated in their study were adequate for orthopedic applications.

In 2020, Sainz *et al.* prepared Si_3N_4 ceramic scaffolds intended for bone tissue engineering by direct ink writing (DIW),[46] which was also a kind of MEX 3D printing, as shown in Fig. 12a. Si_3N_4 ceramic scaffolds reached densities above 95%, as shown in Fig. 12b and c. The bioactivity of these structures was addressed by evaluating the ion release rate in simulated body fluid. In parallel, atomic force microscopy was used to determine the effect of the filaments surface roughness on protein adsorption (Bovine Serum Albumin) for assessing the potential application of MEX 3D-printed Si_3N_4 ceramic scaffolds in bone regeneration.

An improved screw extrusion fused deposition modeling (FDM), which is also a type of MEX 3D printing, was reported to

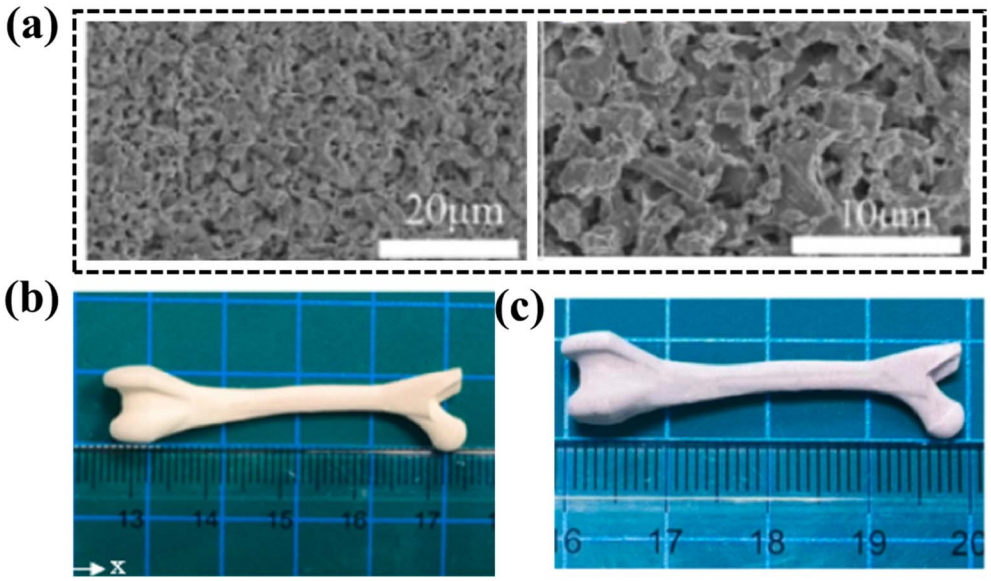

Fig. 10 (a) Porous microstructure, (b) green bone, and (c) sinter bone of VPP 3D-printed porous Si_3N_4 ceramic.[44]

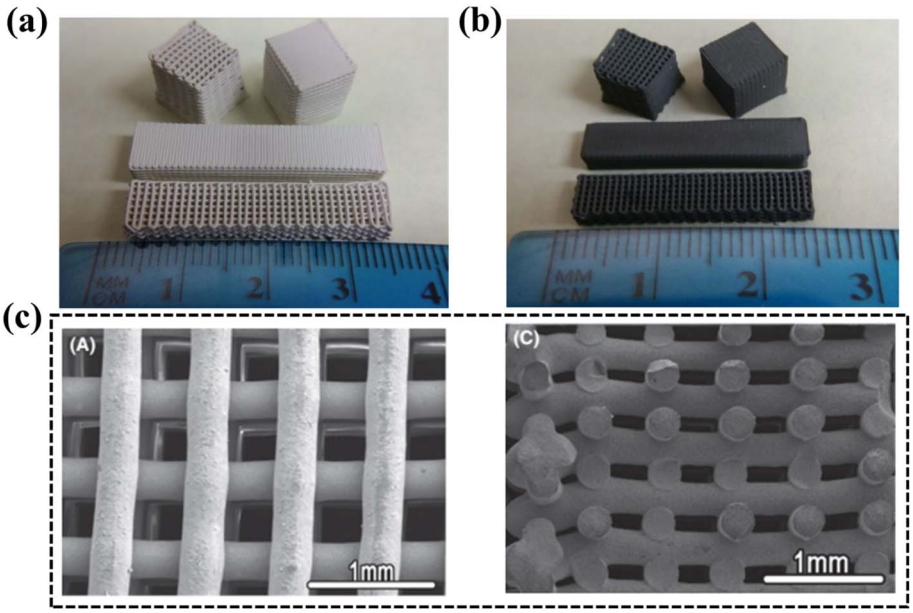

Fig. 11 (a) MEX 3D-printed Si_3N_4 ceramic green parts, (b) sintered parts, and (c) microstructures of the architecture.[45]

fabricate Si_3N_4 ceramic (as given in Fig. 13a).[47] The authors used 3D printing to achieve customized molding and gas pressure sintering to prepare dense Si_3N_4 ceramic and investigated the mechanical properties as well as biological activity. Compared with Ti-alloy, Al_2O_3, and PEEK, 3D-printed Si_3N_4 ceramic had significant advantages in mechanical properties with a bending strength of 803 MPa, a fracture toughness of 8.86 MPa $m^{1/2}$, a Vickers hardness of 15.1 GPa, and a compressive strength of 2725 MPa. Meanwhile, the MEX 3D-printed Si_3N_4 ceramic had an excellent and more stable biocompatibility compared to biomedical materials and had obvious advantages in antibacterial performance, with an antibacterial rate of 94.6% (as illustrated in Fig. 13b). On the surface of MEX 3D-printed Si_3N_4 ceramic, cells had good morphology and normal migration and were more conducive to cell spreading, adhesion, and cross-linking. Their study showed that the melting deposition filling characteristics of the 3D printing method, the crystal-oriented growth microstructure characteristics of 3D-printed Si_3N_4 ceramic, and the beneficial effects of silicon and nitrogen elements were the main reasons for achieving these advantages.

In fact, except for the aforementioned 3D printing, other 3D printing technologies, such as SLS, DED, and so on, can also be applied to the 3D printing of Si_3N_4 ceramic implants. Indeed, dense or porous Si_3N_4 ceramic has been widely reported to be 3D-printed using different technologies.[48–51] We believe that there will be more reports on the Si_3N_4 ceramic prepared by different 3D printing technologies and more studies on their microstructure, mechanical properties, biological properties, and real clinical applications.

4. Challenges and prospects

Although the 3D printing of Si_3N_4 ceramic implants has achieved great developments, there are still many aspects that need to break through in the near future to advance their real clinical applications.

4.1 High mechanical properties

Generally, ceramic orthopedic implants need to have excellent mechanical properties, including high mechanical strength,

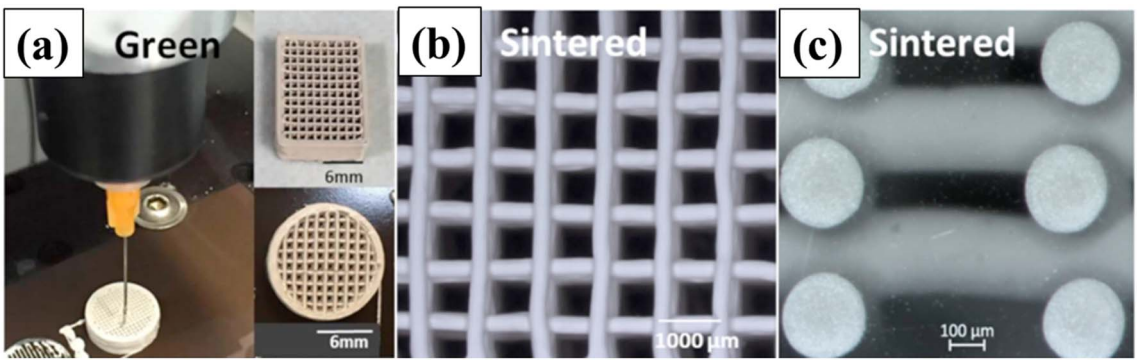

Fig. 12 (a) DIW MEX 3D printing of Si_3N_4 ceramic scaffolds and (b and c) microstructures of the green and sintered parts.[46]

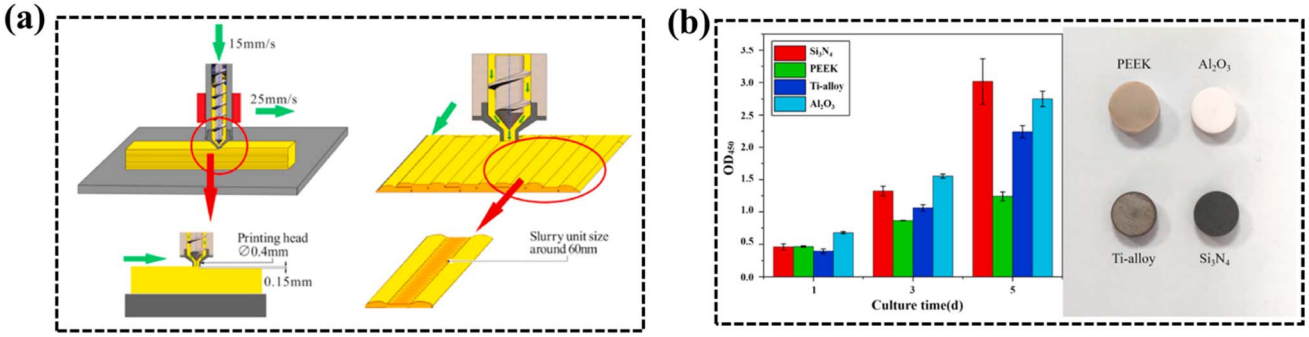

Fig. 13 (a) Improved screw extrusion fused deposition modeling (FDM); (b) excellent biocompatibility of the 3D-printed Si_3N_4 ceramic.[47]

high fracture toughness, good fatigue performance, good creep performance, *etc*.

On the one hand, the strength and toughness need to improve. Table 3 lists some of the reported strength and fracture toughness of 3D-printed Si_3N_4 ceramic. Fig. 14 further gives the comparison of the relative density and strength of 3D-printed Si_3N_4 ceramics by different 3D-printed methods (some relative density or strength data are missing in the references). It is clearly found that most of the 3D-printed Si_3N_4 ceramics had a relatively low density, low strength, and low toughness relative to traditional sintered dense Si_3N_4 ceramic (usually >99.9% density and >800 MPa strength)[48,49,61] and ZrO_2 ceramic (usually >99.9% density and even >1000 MPa strength)[62,63] for clinical implant applications. Fortunately, some studies achieved high-performance Si_3N_4 ceramic using 3D printing. In order to apply it to real applications in the human body, especially the hips, knee, and dental implants, both high strength and high toughness are needed. Therefore, how to further improve the mechanical properties of materials, especially the strength and toughness, will be the future research focus. On the other hand, in actual human implantation environments, ceramic implants need to withstand fatigue, creep, and other service environments. Unfortunately, there has been no report about the fatigue and/or creep behavior of 3D-printed Si_3N_4 ceramic so far. How to improve the fatigue resistance and creep resistance of 3D-printed Si_3N_4 ceramic implants will also be the future focus for applications.

4.2 Composites

Compositing ceramic materials with other materials (such as polymers, metals, *etc.*) is another path to achieving high-performance implants. In 2021, Marin *et al.* prepared PMMA/Si_3N_4 composites by VPP 3D printing and investigated their antibacterial effects.[64] In 2023, Vidakis *et al.* also prepared polylactic acid/Si_3N_4 nanocomposites by MEX 3D printing, and their biodegraded and biomedical behaviors were further discussed.[65] In 2023, Afrouzian *et al.* fabricated Si_3N_4-reinforced Ti_6Al_4V composites by direct energy deposition (DED) 3D printing technology and studied their bio-tribo-corrosion and antibacterial properties.[66] However, more detailed studies about the 3D-printed composite implants need to be performed.

Moreover, the 3D printing of organic composite implants with ceramics is currently the most promising candidate for bone/chondral repair. Usually, the organics, such as hydrogels

Table 3 Strength and fracture toughness of 3D-printed Si_3N_4 ceramics

Material	3D printing	Relative density (%)	Strength (MPa)	Fracture toughness (MPa $m^{1/2}$)	Ref.
Si_3N_4	VPP	99.4	323[a]	—	52
Si_3N_4	VPP	88.43	57.3[b]	—	53
Si_3N_4	VPP	95	—	5.82	54
Si_3N_4	VPP	85.4	149.2[b]	—	55
Si_3N_4	VPP	95.8	—	6.57	56
Si_3N_4	VPP	99.8	764[c]	—	42
Si_3N_4	VPP	—	770[b]	13.3	43
Porous Si_3N_4	VPP	41.52	79[d]	—	44
Si_3N_4	MEX	—	552[b]	—	45
Si_3N_4	MEX	—	803[b]	8.86	46
Porous Si_3N_4	MEX	60–70	53[b]	—	57
Porous Si_3N_4	BJ	63.98	47[b]	—	58
Porous Si_3N_4	BJ	39	95[b]	2.4	59
Si_3N_4	LOM	93.7	475[b]	—	41
Si_3N_4	LOM	99.72	725 ± 26[b]	7.6 ± 0.4	60

[a] 3-Point flexural strength. [b] 3-Point flexural strength. [c] Biaxial strength. [d] Compressive strength.

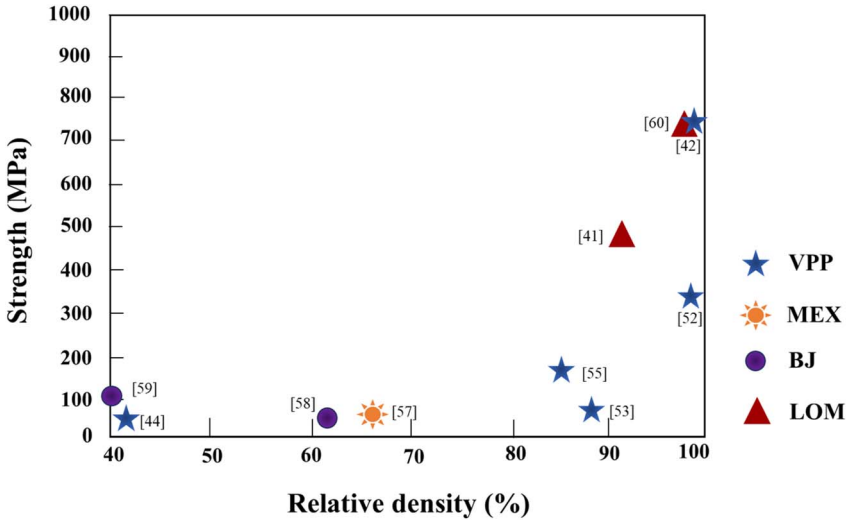

Fig. 14 Comparison of the relative density and strength of 3D-printed Si_3N_4 ceramics by different 3D-printed methods (some relative density or strength data are missing in the references).[41,42,44,52–60]

and polymers, provide a cell-like living environment that more closely resembles natural tissue. In the future, *in vitro* and *in vivo* experiments of the 3D-printed bioceramic/organic implants need to be extensively investigated.

4.3 Drug loading

In order to further improve the biocompatibility of the 3D-printed Si_3N_4 ceramic implants, loading them with bioactive factors, such as drugs, is an effective approach. Conventional drug therapy often requires systematic administration of higher doses to achieve the therapeutic dose for the target tissue, resulting in the entire body being affected by side effects. A significant benefit of local drug release is that adequate drug doses can be obtained over a longer period at hard-to-reach sites of action with minimal side effects. Fig. 15 shows the schematic of drug release from the scaffold during bone repair.[67] Drug loading will be an important topic of the 3D-printed Si_3N_4 ceramic scaffold implants in future work. It has been demonstrated that biopolymer scaffolds[68,69] and bioceramic scaffolds (hydroxyapatite[70] and tricalcium phosphate[71]) are supportive of

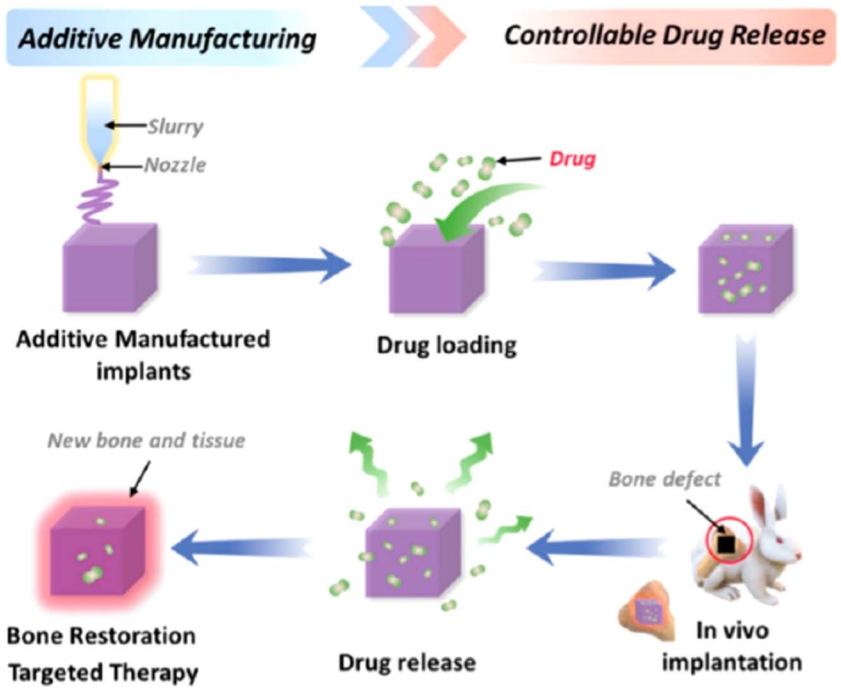

Fig. 15 Schematic representation of drug release from the scaffold during bone restoration.[67]

drug release, which gives a good reference for 3D-printed Si_3N_4 implants.

4.4 Economics and low cost

Of course, current implants are basically made of polymers, metals, *etc.* The real clinical application of ceramic implants, especially silicon nitride ceramic implants, still faces the challenge of high costs and high prices. How to reduce the price of medical-grade Si_3N_4 powders, how to improve the efficiency and reduce the cost of 3D printing of Si_3N_4 ceramic, and how to reduce the cost of biological and clinical evaluation will be the key to the next step in the clinical application of Si_3N_4 ceramic implants.

5. Conclusions

Si_3N_4 ceramic is an attractive ceramic implant material in healthcare, particularly in orthopedic surgery. With the advancement of 3D printing technology, Si_3N_4 ceramics can now be fabricated into customized implants with precise anatomical shapes, sizes, and microstructures, catering to the individual needs of patients. Therefore, we conducted a comprehensive review of how 3D printing enables complex-shaped Si_3N_4 ceramic implants for clinical applications, with the aim of providing helpful guidance for related scientists, clinicians, and dentists in this field. The main conclusions are as follows:

(1) There are seven categories of 3D printing, including VPP, MEX, MJ, BJ, PBF, DED, and SL, that are used to prepare complex-shaped ceramic components. Among them, VPP, MEX, and BJ are the most used 3D printing methods for Si_3N_4 ceramic.

(2) The recent state of the art in novel 3D-printed Si_3N_4 ceramic implants was summarized. The most common 3D-printed Si_3N_4 ceramic implants for biomedical applications are mainly obtained by VPP and MEX 3D printing.

(3) Challenges toward 3D printing of Si_3N_4 ceramic implants are discussed. It is clearly found that most of the 3D-printed Si_3N_4 ceramic had a relatively low density, low strength, and low toughness compared to traditional sintered dense Si_3N_4 ceramic and ZrO_2 ceramic for clinical implant applications. How to improve the density, strength, toughness, as well as fatigue resistance and creep resistance of 3D-printed Si_3N_4 ceramic implants will also be the future focus for applications.

(4) Prospects for the 3D printing of Si_3N_4 ceramic implants, such as composites and drug loading, were further analyzed.

Data availability

All data included in this study are available upon request by contacting the corresponding author.

Conflicts of interest

There are no conflicts to declare.

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