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Recent advances in 3D printing of porous ceramics: A review

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ABSTRACT

3D printing, alongside the rapidly advancing field of porous ceramics, is quickly expanding the horizon of what is going to be possible in the future. In this paper, 3D printing technology is evaluated for its compatibility with porous ceramic materials, due to its competitive process in terms of speed and specific tooling, especially for good quality fabrication. The paper reviews the capabilities of these new technology techniques for the fabrication of porous ceramic. The basic technology is the 3D printing techniques, which are used to fabricate porous green ceramic parts that are later sintered. Different ceramic materials are evaluated and the classification of different powders according to their 3D printing quality as well as material aspects is examined. The evaluation of 3D printing process in terms of the powders' physical properties such as particle size, flowability and wettability is also discussed. The relationship between the different 3D printing parameters and the final printing outcome are assessed.

1. Introduction

Three-dimensional printing (3D printing) is a highly customizable technology, which is changing the ways to approach the problem of porous ceramic fabrication. The applications include customized surgical tools, patient specific prostheses, scaffolds, dental porcelain and porous ceramic filter fabrication [1–3]. 3D printing can be defined as a layer upon layer fabrication technology using material deposition in order to build up different geometrical shape of 3D components [3–5]. It is becoming known as direct digital fabrication, which uses CAD software to exactly determine how each layer will be constructed and prints objects through fusing a variety of materials (powder and binder, in the case of 3D ceramic printing) [6,7]. In this technique, a model is printed in a build platform that is filled with powder material. The liquid binder is applied through an inkjet printer head to the appropriate layer and solidifies the powder. The build platform is then lowered by 0.1 mm and another powder layer is spread over the first, and the process is repeated until the part is complete within the powder bed [2,8].

The microstructure features, such as porosity and pore size distribution are very important factors for various potential applications of porous ceramics. Porous ceramics with different porous morphology and size distribution can be fabricated by different methods, for example, burning out a polymeric sponge impregnated with a ceramic slurry, solid state sintering, a sol-gel process, replication of polymer foams by impregnation, and gelcasting processes [9]. Introducing the 3D printing technology for porous ceramics offers increased flexibility and speed, eliminates tooling constraints, requires only low cost investment and also enables sustainability of the fabrication process [10–14].

Conventional porous ceramic fabrication faces many challenges to fabricate a fully interconnected pore network in terms of the need for highly toxic organic solvents, incomplete removal of residual particles in the polymer matrix, irregularly shaped pores, insufficient interconnectivity of pores, and thin structures; these difficulties mean there is poor repeatability, it is time consuming, and needs a large labor force [15]. Some examples of conventional methods include fiber bonding, solvent casting and particulate leaching, membrane lamination, melt molding and gas foaming. Even by casting or molding, it is difficult to easily and independently control the porosity and pore size of the porous ceramic, besides their restrictions on shape control [16].

The promise of 3D printing is based on customized parts that are typically made to order in unique configurations and in very small quantities. The use of the internet further enhances the possibilities of design sharing and modifications; thus the porous ceramics can be printed anywhere. According to Seitz et al. [17], 3D printing is well suited to fabricate complex porous ceramic

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Nomenclature

C_d	cure depth	σ_L	liquid surface tension
D_p	light penetration depth	η_L	liquid dynamic viscosity
E	light irradiation dose	V_α	volume of ethanol
E_c	critical energy	V_β	volume of ethanol vacuum forced into the pores of scaffolds until no bubbles appeared
ΔP	pressure loss	V_γ	remained volume of ethanol
μ	dynamic viscosity	P	porosity
L	length of extruder	l_z	vertical pore size
Q	volumetric flow rate	l_{xy}	Horizontal pore size
d	nozzle diameter	L_α	two adjacent distance between horizontal strand centers
X_L^*	weight fraction of large particles	D	diameter of the strand
f_L	large particles fractional packing density	R	pore radius
f^*	best composition of fractional packing density	D_b	pores distance
f_s	small particles fractional packing density	P_N	numbers of pores
ff_β	flow factor	S_A	bulk surface area
σ_1	consolidation stress	S	shape (circular or hexagonal)
σ_2	compression strength	E_s	compressive stiffness
m	absorbed liquid mass	σ	yield strength
t	time of Absorption	C_1, C_2, n	constants
c	capability constant		
ρ_L	liquid density		

matrices directly from powdered materials. Due to its capability for complexity, several studies have investigated the application of 3D printing for scaffold fabrication for tissue engineering [18–20].

Due to the enhancements in detail, precision and surface finish, 3D printing has been progressively used for such medical applications. Individual porous scaffold, which resembles natural bone structure, unique in size and shape, have recently been developed for use in 3D printing [21–23]. A study made by Zhange et al. [1], explored the feasibility of using a 3D printing process for a high accuracy fabrication of dental ceramic porcelain structures. However, the 3D printing process has a number of control parameters that can significantly affect the fabrication quality. In many cases, materials are supplied as powders and their characteristics such as particle size, shape and distribution will significantly influence the resulting structure and thus impact on the properties of the porous ceramic [24].

In 3D printing technology, larger ceramic particles are easily spread layer by layer. They have lower surface-volume ratio and larger pores, which results in the fabrication of more homogeneous ceramic parts. This is because the binders are able to form better bonding between particles inside the powder bed. On the other hand, finer ceramic particles produce thinner layers, lower surface roughness and promote printability [25]. Similarly to the microsintering process, thinner layers and correspondingly smaller particles sizes are required to achieve a finer matrix. 3D printing has demonstrated a good applicability for 3D microfabrication by taking advantage of the using of ceramic particles as a substrate in each layer [26]. Furthermore, advancements in the bonding between layers, dimensional stability, surface finish and resolution would be advantageous for 3D printed porous ceramics, especially in the micro- and nanofabrication fields.

A literature review by Campbell et al. [27] found that ceramic nanoparticle materials can lead to improvements in mechanical properties (tensile strength and modulus) of the final porous parts. Although there are a range of significant technical and scientific challenges to integrating the use of nanoparticles with 3D printing technology, this integration will enable their effective use for porous ceramics, especially for bone tissue engineering [28]. Different materials such as silica make the parts stiffer but brittle, whereas alumina can enhance the sintering characteristics.

As the overall, aim of this review is to explore 3D printing technology for its compatibility to print porous ceramics, the focus is on the 3D printing mechanism and its process to fabricate porous ceramics, as well as the applications, future trends and demand for high quality 3D printed porous ceramics. Parameters that can affect porous ceramics are also discussed, to characterize their performance further. A new approach to the design and fabrication of porous ceramics for tissue engineering using 3D printing is investigated, and also its biocompatibility and suitable mechanical properties for highly interconnected porous networks.

2. 3D printing technology processes

3D printing employs an additive manufacturing process in which the printer uses the ceramic powder which is deposited on a build platform and prints a geometrical model based on layer by layer fabrication technologies. It is a process of making three dimensional solid objects from a digital stereolithography file format (STL file). It builds up components from nothing, layer by layer, until the part is complete. Fig. 1 shows the graphical representation of the information in an STL file. The porous material on the left, was created in a CAD program and was subsequently saved as an STL file. The same material, on the right, is displayed triangulately, as the graphical information in the STL file. The spatial coordinates of the triangle vertices are contained in the STL file, and that information is transmitted to the printer for fabrication. A 3D printer device which presents a high number of triangles and vertices means that more data points were used to spatially define the part's surface, and thus increase the resolution of the printer device.

The 3D printing process is based on printing technology. It is a process which turns digital 3D models into solid objects by building the material layer by layer. Most commonly, 3D printing uses a powder-based method where solid particles are bound together by a binder material to generate a shape of part. The 3D printing process is illustrated in Fig. 2. The powder is generally distributed evenly onto the build platform by a powder-spreading roller. A liquid binder is deposited onto the powder layer, using a printer head. Whenever the liquid binder is applied to the powder, the particles are joined together. After the first layer is completed, the build