

3D 打印制备羟基磷灰石-镁黄长石分级螺旋结构骨支架

化帅斌^{1,2}, 彭畅^{1,2,3}, 程立金⁴, 吴甲民^{1,2,3}, 张笑妍⁵, 王秀梅⁶, 史玉升^{1,2}

(1. 华中科技大学材料科学与工程学院, 材料成形与模具技术全国重点实验室, 武汉 430074; 2. 增材制造陶瓷材料教育部工程研究中心, 武汉 430074; 3. 华中科技大学温州先进制造研究院, 浙江 温州 325035; 4. 河北工业大学先进装备研究院, 天津 300401; 5 北京科技大学先进材料技术研究院 北京 100083; 6 清华大学, 新型陶瓷材料全国重点实验室, 北京 100084)

摘 要: 性能良好的松质骨种植体需要同时具备高孔隙率和良好的机械性能, 但这很难通过均一的结构来实现。采用数字光处理技术打印了一系列径向内孔隙率为 50%、外孔隙率为 70% 的分层状羟基磷灰石-镁黄长石支架, 用以模拟松质骨结构和性能。随着过渡直径的增大, 弹性模量增大, 骨支架的抗压强度提升。当过渡直径达到支架直径的 75% 时, 抗压强度超过 2 MPa。在降解过程中, 镁黄长石释放出的离子和微孔的存在使 G75 支架在第一天的降解率较快(5.73%), 这使得支架的抗压强度略有下降。随着浸泡时间的持续增加, 降解速度减慢, 14 d 时由于磷灰石的沉积, 支架的重量和抗压强度上升。最后, 精确制备了具有松质骨几何形状的分层陀螺支架, 其最大载荷比均匀结构高 8 倍。

关键词: 生物陶瓷; 分级结构; 抗压强度; 生物活性; 数字光处理
中图分类号: G301 文献标志码: A 文章编号: 0454-5648(2025)09-2706-12
网络出版时间: 2025-08-25



1 Introduction

Many individuals are affected by bone defects due to accidents and medical conditions, including trauma, congenital malformations, or surgeries to remove tumors^[1-3]. Fortunately, artificial bone scaffolds are used for bone repair, thus offering the advantages of a readily available supply and lack of rejection reactions^[4-5]. An idealized bone scaffold should exhibit structural and mechanical properties that are analogous to those of cancellous bone. These include the capacity to facilitate bone repair, biodegradability, and mechanical properties that are conducive to the repair of bone and the maintenance of mechanical stability^[6-9]. To prepare a scaffold with superior performance, scholars mainly focus on studies of the structure of bone scaffolds^[10-12]. It is

indicated that the interconnected pores and the high porosity structure are conducive to cell ingrowth, survival, and angiogenesis^[13-15]. However, a high porosity often leads to a poor mechanical strength, and it cannot even meet the requirements of application^[15-17]. Thus, some species of gradient structures with a functional anisotropy are designed to solve this problem^[18-19]. It is expected to prepare gradient bone scaffolds that are suitable for bone growth and provide adequate support.

Though conventional technologies such as modified freeze-casting techniques and electrospinning techniques can be used to fabricate gradient scaffolds, they cannot control porosity and pore size accurately^[20-22]. Additive manufacturing (AM) technologies have a capacity to fabricate objects in a layer-by-layer manner, thereby enabling the fabrication of designed complex gradient

收稿日期: 2024-09-24。 修订日期: 2024-11-11。

基金项目: 温州市基础科学研究项目(G20240008); 北京自然科学基金(L212020); 清华大学新型陶瓷与精细加工国家重点实验室开放课题(KF202301); 中央高校基本科研基金(2024JCYJ068, 15882024XCZX002)。

第一作者: 化帅斌(1998—), 男, 博士研究生。

通信作者: 吴甲民(1984—), 男, 博士, 教授。

Received date: 2024-09-24. Revised date: 2024-11-11.

First author: HUA Shuaibin (1998—), male, Doctorial Candidate.

E-mail: 459912636@qq.com

Correspondent author: WU Jiamin (1984—), male, Ph.,D, Professor.

E-mail: jiaminwu@hust.edu.cn

porous structures^[23–25]. As one of the gradient structures, radial-gradient porous structures can be classified into two types, *i.e.*, porosity increases or decreases from inner layers to outer layers. Di Luca *et al.*^[26] used a direct ink writing process to print a scaffold with an interconnected porosity gradient to mimic natural cancellous bone. They found that different zones within the scaffold displayed varying levels of osteogenic differentiation. Li *et al.*^[25] designed two kinds of radial gradient structures *via* changing the strut thickness (*i.e.*, 0.2–0.4 mm), then the scaffolds with an increase or a decrease porosity from outside to inside were printed, both showing enhanced mechanical properties, compared to uniform scaffolds (0.2 mm). Lindner *et al.*^[27] prepared porous scaffolds *via* 3D printing and lost wax casting techniques to improve the strength of scaffolds. Liao *et al.*^[28] fabricated linear porosities scaffolds with triply periodic minimal surface (TPMS) that were similar to human bone, and the mechanical properties of samples met requirements of natural cancellous bone.

Although porous scaffolds can be prepared by 3D printing, how to design porous structures to better achieve an effective match between osteogenesis and mechanical property is also a challenge^[29–30]. The porosity and pore size are important for bone in-growth^[31] osseointegration^[32], and promote a good mechanical interlocking^[33] between the adjacent bone and scaffolds. Lim *et al.*^[31] printed HA/TCP ceramic scaffolds with different porosities, and found more bone formation in scaffolds with larger pore sizes after four weeks. Lewandrowski *et al.*^[34] reported that scaffolds with a high porosity had a deeper and greater bone ingrowth. Therefore, the radial-gradient structures with a high porosity outside and a significant distribution of porosity are expected to repair bone defects more effectively.

In this paper, we chose TPMS structures (such as gyroid) that could retain a high stiffness^[35], and have a great potential to design complex hybrid structures^[36–37]. A series of hierarchical gyroid structures with a significant gradient porosity from outside (*i.e.*, 70%) to inside (*i.e.*, 50%) were designed through smooth structural transitions to simulate the structure and

properties of cancellous bone. Hydroxyapatite (HA) & 10% (in mass) akermanite scaffolds were fabricated *via* digital light processing (DLP)^[38]. In addition, the properties of scaffolds with different transition diameters were also investigated.

2 Experimental

2.1 Starting materials

$\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2$ (hydroxyapatite, purity >98% in mass) and $\text{Ca}_2\text{MgSi}_2\text{O}_7$ (akermanite, purity >98%) from Kunshan Co., Ltd., China, were chosen as bioceramics powders. The composite bioceramic powders contained 10% akermanite and exhibited superior mechanical properties and bioactivity. All other materials could refer to a previous work^[38]. Tris-HCl and simulated body fluid (SBF) from Phygene Life Sciences Co., China, were used to explore the degradation properties and *in-vitro* properties of bioceramic scaffolds. The content and concentration of ions in the SBF solution were the same as a previous report from Kokubo *et al.*^[39]

2.2 Hierarchical gyroid structure design

The basic function of gyroid TPMS is shown as

$$\begin{aligned} &\cos(\alpha x) * \sin(by) + \cos(by) * \\ &\sin(cz) + \cos(cz) * \sin(\alpha x) + d(x, y, z) = 0 \end{aligned} \quad (1)$$

where a , b and c are cell size parameters, which are used to adjust the length-width ratio of the pore, and d is cell shape parameter, which is used to adjust the proportion of pores in the cell. In this work, two functions of $d(x, y, z)$ are set to constants 0 and 0.608, which correspond to 50% porosity and 70% porosity, being abbreviated to Gyroid 50% porosity (G_{50p}) and Gyroid 70% porosity (G_{70p}), the values of a , b , and c are set to 1.

Fig. 1 shows the flowchart of the hierarchical gyroid structures design. G_{fusion} can be defined as Eq. (2) to smoothly connect two pore morphologies. Two homogeneous Gyroid structures with different porosities of 50% and 70% are correlated to a parameter $\alpha(x, y, z)$. Meanwhile, sigmoid function (SF)^[36] for $\alpha(x, y, z)$ is used to design a hybrid gyroid structure (see Eq.(3)). The parameter r in Eq. (3) can be used to adjust the transition radius.

$$G_{\text{fusion}} = \alpha(x, y, z)G_{70p} + (1 - \alpha(x, y, z))G_{50p} \quad (2)$$

$$\alpha(x, y, z) = \frac{1}{1 + e^{-3(x^2 + y^2 - r^2)}} \quad (3)$$

where $x^2 + y^2 - r^2 = 0$ is the transition boundary to connect the G_{50p} and G_{70p} structures. When $x^2 + y^2 \geq r^2$, $\alpha(x, y, z)$ is close to 1 and $G_{\text{fusion}} = G_{70p}$. Conversely, $\alpha(x, y, z)$ is close to 0 and $G_{\text{fusion}} = G_{50p}$. When the diameter d of the scaffold is unchanged (or the value range of x and y is unchanged), the transition boundary position can be adjusted *via* adjusting the value of r . The larger the r is, the fewer the values that meet the condition $x^2 + y^2 \geq r^2$ will be. The transition boundary is close to the edge of the scaffold, and the structure is close to the uniform Gyroid structure with a porosity of 50%. On the contrary, when r is 0, the condition $x^2 + y^2 \geq r^2$ is a constant, and the whole scaffold is a uniform Gyroid structure with a porosity of 70%. Therefore, different transition boundary bracket models were obtained according to different r values. Gyroid surfaces were generated in the k3dsurf software, and the coordinate values were all from -20 to 20 . After that, they were imported into a software named Magics to transform into entities. A cylinder with a diameter of 10 mm was used to subtract them (Boolean operations) and obtain the hierarchical gyroid structures. The ratios of transition diameter to the diameter of scaffolds were set as 0%, 25%, 50%, 75%, and 100%. They were abbreviated as samples G0, G25, G50, G75, and G100. Table 1 shows the specific parameters of different structure types.

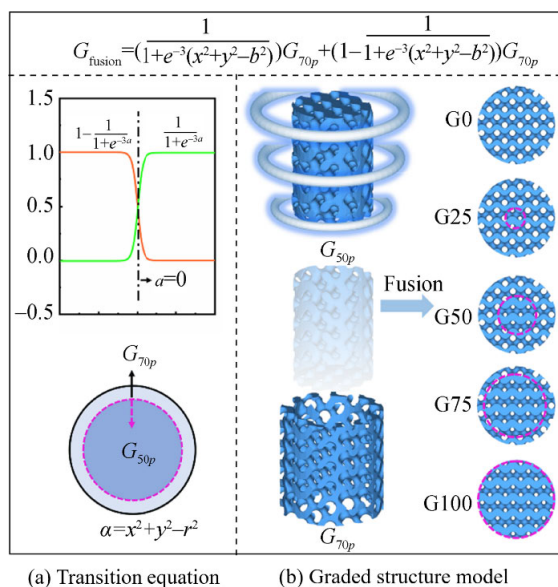


Fig. 1 Flowchart of the hierarchical gyroid structures design

Table 1 Parameters of different hierarchical gyroid structures

Structure type	Value of r	Diameter of scaffolds/mm	Transition diameter	Structure porosity/%
G0	0	10	0% d	70.0
G25	1.25π	10	25% d	68.8
G50	2.5π	10	50% d	64.9
G75	3.75π	10	75% d	58.7
G100	5π	10	100% d	50.0

2.3 Bioceramic scaffolds preparation

The models of scaffolds were imported into the DLP printer with a 405-nm light. Composite material HA & AK (akermanite) was selected for a scaffold, and the photosensitive resin was a double resin scheme of TPGDA and HDDA. The specific slurry formulation and preparation method could be referred to a previous research^[38]. The samples were printed with the intensity of 8 mJ/cm² and a layer thickness of 50 μm . Finally, the ceramic samples were sintered at 1100 $^{\circ}\text{C}$.

2.4 Quasi-static simulation method of hierarchical gyroid structures

A deform software was employed to simulate the distribution of compression stress and elastic modulus for a variety of models. Fig. 2 shows the pretreatment of compressive simulation (G50). In Fig. 2, the mesh was well divided to 35000 elements. Subsequently, the scaffold was set to elastic, and a rigid body was positioned at the apex of the scaffold with a displacement of 0.2 mm. The remaining rigid body was fixed at the base of the scaffold as a platform. The material was built with the Young modulus of 1000 MPa and the Poisson ratio of 0.3. A compression speed was set to 8.3×10^{-3} mm/s, which corresponds to the actual situation. At last, the simulation was divided into 100 equal steps and the stress and strain of the top rigid body were recorded.

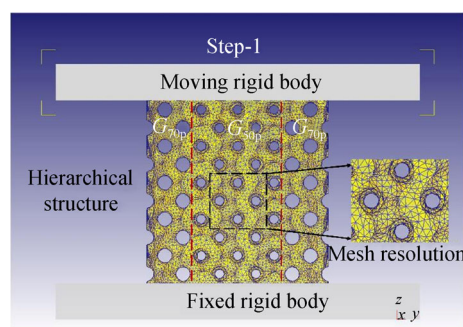


Fig. 2 Pretreatment of compressive simulation (G50)

2.5 Characterizations

The morphologies were determined by scanning electron microscopy (Quanta650, Quanta Group, USA). The phases were characterized by X-ray diffraction (XRD, X'pert3 powder, PANalytical B.V., the Netherlands). The compressive strength of hierarchical gyroid bioceramics scaffolds was characterized by a material testing machine (Zwick Z020, Zwick GmbH, Germany).

The degradability of the hierarchical gyroid bioceramic scaffolds was evaluated through immersion in Tris-HCl solution^[40] and SBF solution^[41] at a ratio of 200 mL/g. The bioactivity of bioceramic was obtained by immersing them in SBF solution for two weeks. The concentrations of calcium, phosphate, silicon, and magnesium ions in the soaking solution were analyzed by inductively coupled plasma optical emission spectrometry (Prodigy Plus, Teledyne Leeman Labs., USA).

3 Results and discussions

3.1 Macro-morphology of hierarchical gyroid bioceramic scaffolds

Fig. 3 shows the macro-morphology of printed green bodies of bioceramic. Clearly, the hierarchical gyroid scaffolds exhibit an interconnected pore structure, and a concomitant decrease in structure porosity as the transition diameter increases. The structural characteristics (*i.e.*, pore size and porosity distribution) of bioceramic green bodies can be aligned with the models to a reasonable extent. Nevertheless, there are still some intrinsic defects (such as reduced

hole size) that are caused by light scattering^[42].

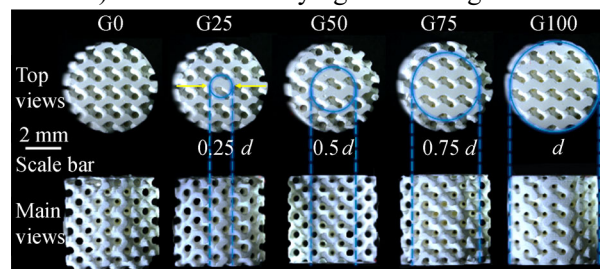


Fig. 3 Macro-morphology of sintered hierarchical gyroid bioceramic scaffolds with different transition diameters

3.2 Micro-morphology and phase composition of hierarchical gyroid bioceramic scaffolds

Scaffolds with different gradients are all prepared by the same process, and have the same composition and microstructure, but there are only differences in structure. G25 scaffolds was selected as the representative for analysis. Fig. 4 shows the SEM images, EDS spectra and XRD patterns of hierarchical gyroid bioceramic scaffolds. In Fig. 4(a), the G25 scaffold exhibits the interconnecting pores, and the strut has a ladder-like morphology due to the layer-by-layer strategy. Also, the transition boundary is smooth between G_{50p} and G_{70p} . In Fig. 4(b), the scaffold exhibits incomplete sintering and a multitude of microscopic pores with a micron-scale diameter. This is because Mg^{2+} substitutes Ca^{2+} in HA to prevent densification^[38]. In Fig. 4(c), a phase $Ca_3(PO_4)_2$ (JCPDS 09-0169) appears after sintering. Furthermore, the overlap of the EDS elemental map of Si and Mg rather than Si and P indicates that there is no reaction between elements Si and P, and akermanite still exists (see Fig. 4(c)).

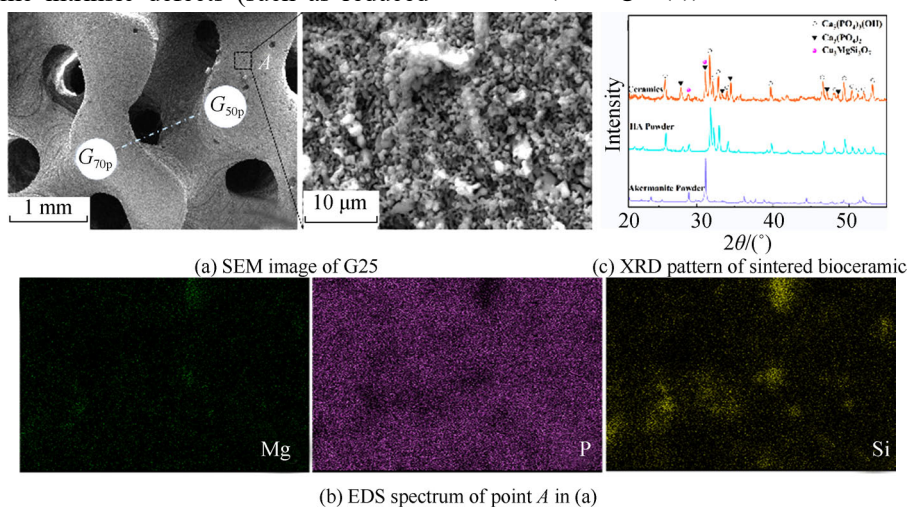


Fig. 4 SEM images, EDS spectra and XRD patterns of hierarchical gyroid bioceramic scaffolds

3.3 Mechanical simulation and experimental results of hierarchical gyroid scaffolds

Firstly, the compressive process of scaffolds was simulated to investigate the stress distribution during the compressive process. Fig. 5 shows the simulation results for stress cloud of G75 at a strain of 2%. In Figs. 5(a) and 5(b), red areas are mainly in the area at a porosity of 50%. The low porosity structures exhibit thick struts that enable them to withstand greater forces

at the same strain, resulting in elevated stress levels. Furthermore, the transition regions are devoid of any discernible red areas, thereby indicating that they are characterized by a smooth transition. Besides, the red section on the fracture surface at 45° is extensive due to the maximum shear stress at 45° from the maximum principal stress when compressed. In Fig. 5(d), the elasticity modulus of scaffolds increases from 80.98 MPa to 239 MPa, and the rate of change accelerates.

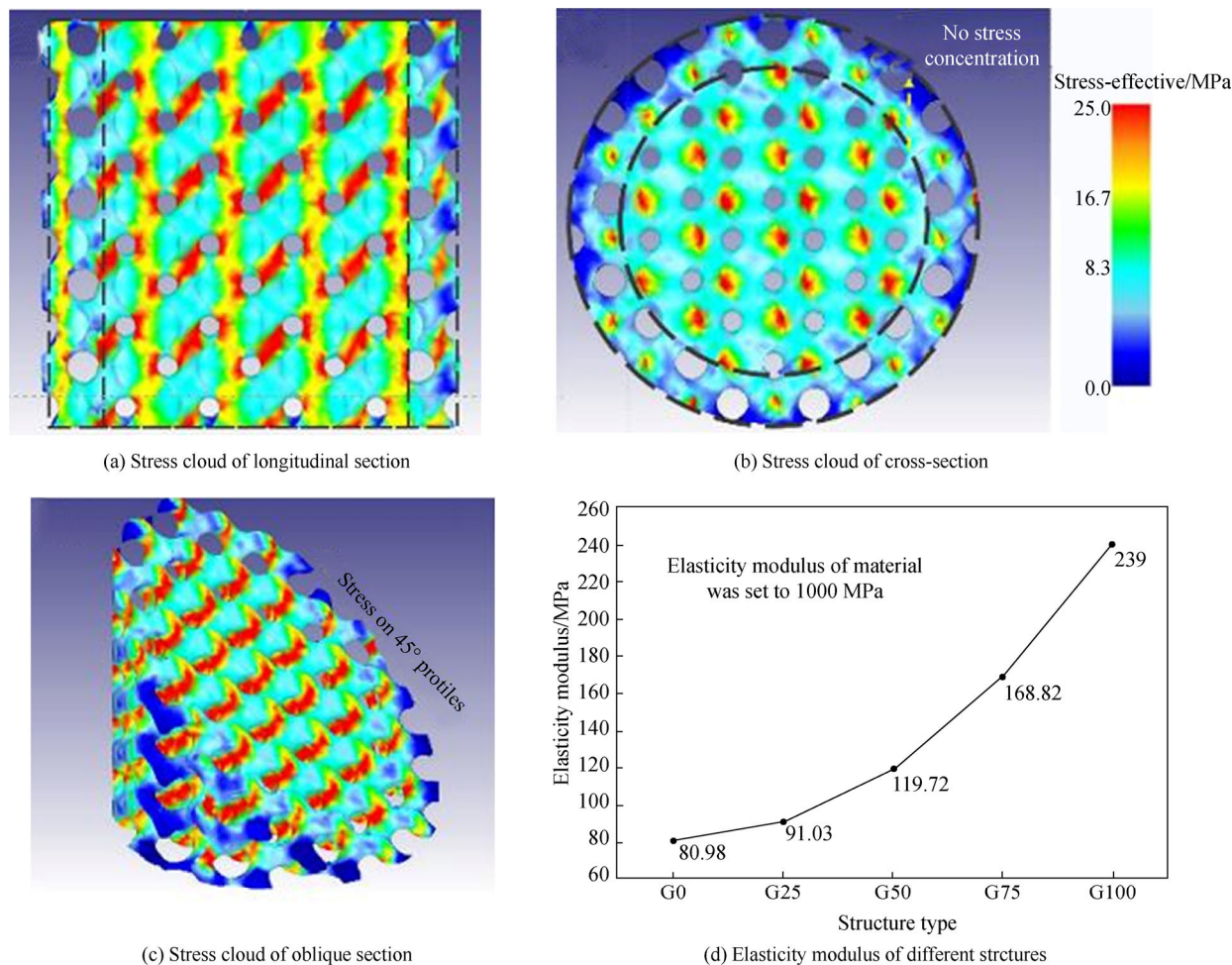


Fig. 5 Simulation results for stress cloud of G75 at a strain of 2%

The suitability of mechanical properties, particularly compressive strength, is of paramount importance in the context of bone repair. Fig. 6 shows the mechanical properties of hierarchical gyroid bioceramic scaffolds. In Fig. 6(a), all bioceramic scaffolds have the features of brittle fracture, and the strains at break of bioceramic scaffolds are near 1.0%. In Fig 6(b), the compressive strength remains constant prior to G50 and subsequently increases gradually as

the transition diameter increases. The compressive strength increases from 0.866 MPa to 2.149 MPa when the structure type changes from samples G0 to G75. Also, all fracture surfaces at 45° to the cylinder axis appear.

The evolution of compressive strength with respect to structure is similar to that of the simulation results for the elasticity modulus. The fracture surfaces indicate that hierarchical gyroid bioceramic scaffolds

have an overall mechanical property due to the natural transition from G_{50p} to G_{70p} (see Fig. 4(a)) and no stress concentration occurs in the transition area (see Figs. 5(a) and 5(b)). Compared to sample G0 scaffolds, sample G75

scaffolds have a higher compressive strength to meet the cancellous bone requirement^[43] (i.e., 2–12 MPa) and the same high porosity outside to promote new bone growth.

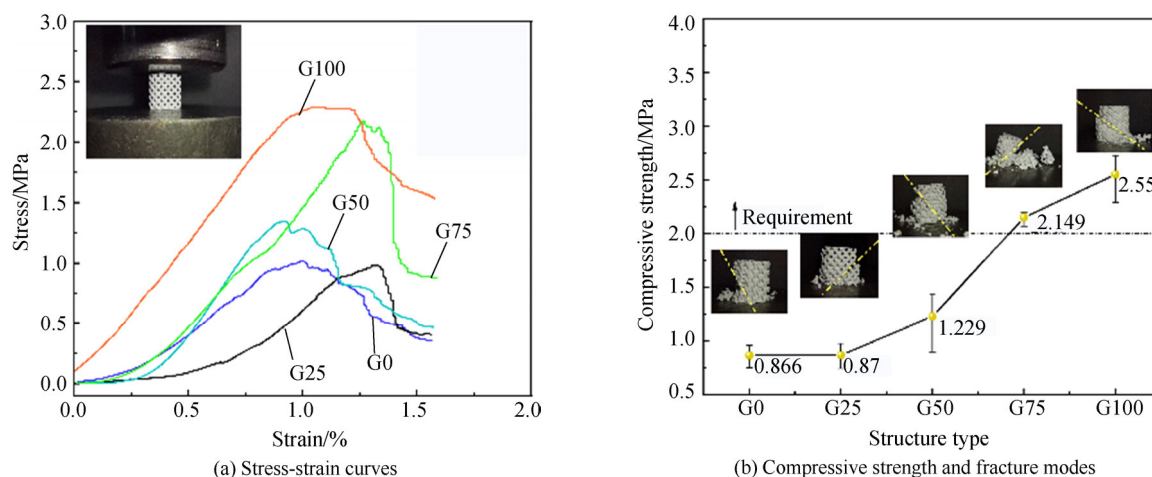


Fig. 6 Mechanical properties of hierarchical gyroid bioceramic scaffolds

3.4 *In vitro* degradation property and bioactivity of hierarchical gyroid bioceramic scaffolds

To investigate the degradation performance of hierarchical gyroid bioceramic scaffolds, sample G75 scaffolds are mainly analyzed and immersed in Tris-HCl for different durations. Fig. 7 shows the surface morphology and cross-sectional topography of bioceramic scaffolds. In Figs. 7(a)–7(d), some nanoparticles are deposited onto the surface of ceramic grains with the

increase of immersion time. Subsequently, the nanoparticles increase in quantity and become discernible to the unaided eye. In addition, the internal ceramic grains are also coated with nanoparticles, with a deposition amount similar to that observed on the surface of the ceramics. These phenomena indicate that the microporous structure of hierarchical bioceramic scaffolds promotes internal contact of bioceramics with degradation solution, leading to an internal degradation.

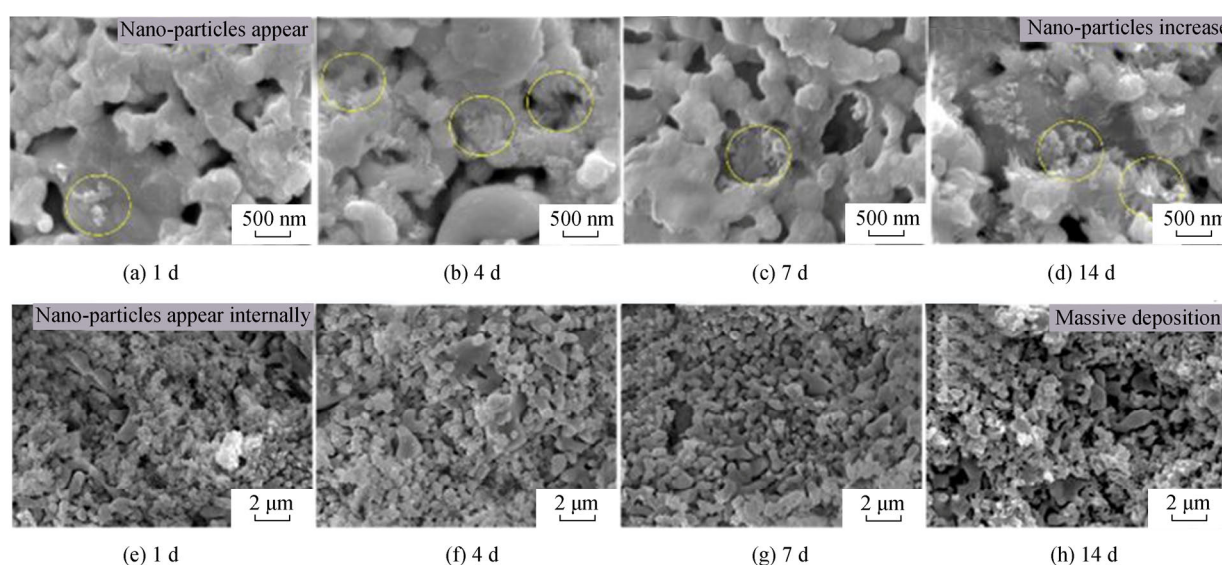
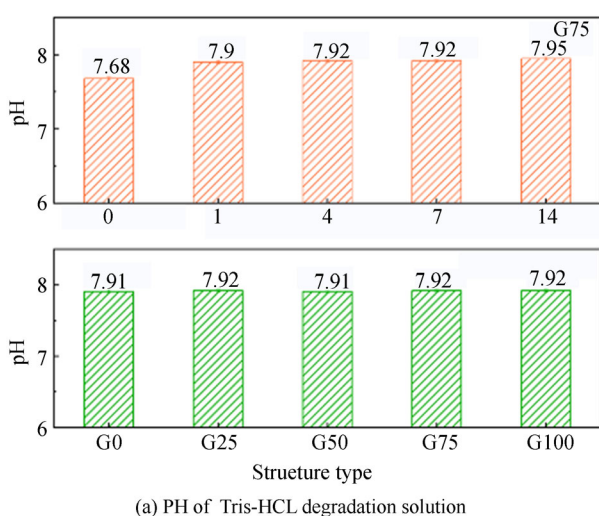


Fig. 7 Surface morphology and cross-sectional topography of bioceramic scaffolds at different immersion durations

Fig. 8 shows the pH value and ion concentration of Tris-HCL degradation solution at different soaking durations (G75) and structural types (soaking for 7 d). In Fig. 8(a), the pH value increases from 7.68 to 7.9 on the first day and then remains stable as the immersion day increases. After 7-d immersing, the pH value of different structures is similar. In Fig. 8(b), after immersion, the concentrations of Ca, Si, and Mg ions rapidly increase before 1st day and reaches a maximum on 4th day, then the concentration decreases slowly. The concentration of P ions increases and reaches its maximum value on 1st day



and then decreases. These phenomena indicate a significant role of $\text{Ca}_2\text{MgSi}_2\text{O}_7$ in bioceramics during the degradation process. On the initial day, Ca, Si, and Mg ions present in $\text{Ca}_2\text{MgSi}_2\text{O}_7$ are released into the solution, resulting in the exchange of H_3O^+ from the solution to the bioceramics. This process leads to an increase in the solution pH value. Si—OH gel layers are formed between H_3O^+ and Si^{4+} , which can absorb Ca^{2+} , PO_4^{3-} , and CO_3^{2-} ions of solution to form apatite or carbonated hydroxyapatite (CHA)^[44–45]. Therefore, akermanite can improve the degradability of bioceramics.

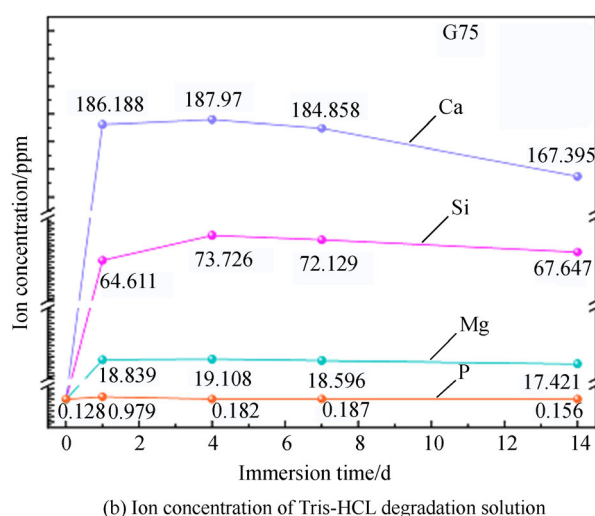


Fig. 8 pH value and ion concentration of Tris-HCL degradation solution at different soaking durations (G75) and structural types (soaking for 7 d)

Fig. 9 shows the degradation rate and compressive strength of hierarchical gyroid bioceramic scaffolds (G75). Clearly, the mass loss of all bioceramic scaffolds firstly increases and then slightly decreases with increasing the immersion duration. After 1-day soaking, the mass loss of hierarchical gyroid bioceramic scaffolds increases to 5.73%, having a superior degradability of scaffolds. The degradation rate slows down gradually with the increase in immersion duration, and a slight increase in weight appears. These results can be since bioceramic scaffolds exhibit a rapid dissolution because of the huge concentration difference of Ca^{2+} , Mg^{2+} , and Si^{2+} between akermanite and SBF solution in the early stage of immersion. The concentration difference declines, leading to a lower release rate of ions. When immersion duration is over 7

d, more and more apatite deposits on the bioceramics and results in an increase in the mass of scaffolds. Note that the hierarchical gyroid bioceramics with different structure types have various surface areas and macro-porosities, but they have the similar degradability.

The compressive strength of scaffolds shows an opposite trend to the degradation rate, which decreases first and reaches its minimum value after immersion for 7 d, and then increases on 14 d of immersion. The weight loss can reduce the compressive strength before immersion for 7 d, and apatite deposition on the 14th d can enhance the struts and compressive strength. These phenomena can indicate the degradation process of scaffolds after *in-vivo* implantation, though the mass and strength decrease during the initial stage, a new bone ingrowth can compensate for these losses.

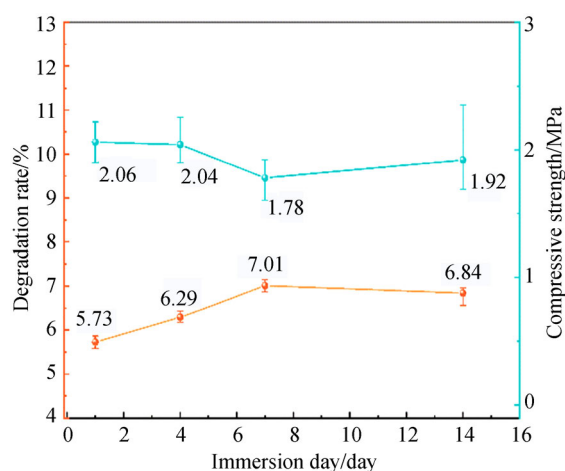
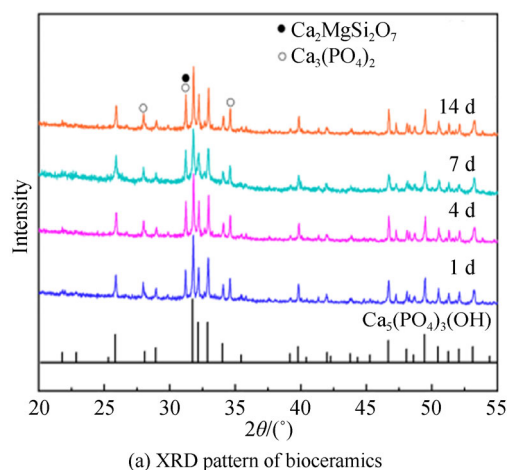
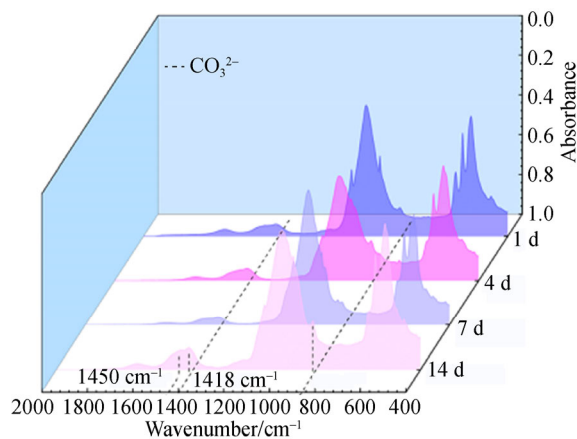


Fig. 9 Degradation rate and compressive strength of hierarchical gyroid bioceramic scaffolds (G75) at different immersion durations



(a) XRD pattern of bioceramics



(b) FTIR spectroscopy of bioceramics

Fig. 10 XRD patterns and FTIR spectra of surface of bioceramics after immersing for different durations

Fig. 11 shows the SEM images and EDS spectra for surface micromorphology of bioceramic scaffolds after different immersion durations. In Fig. 11(a), there are many micropores on the surface of bioceramics before immersing, and the bioceramic grains are smooth. After 1-d immersion, some nanoparticles deposit onto the surface of scaffolds and lead to a decrease in micropores. In Fig. 11(c), there is no ceramic grain and the surface of ceramics is covered by a dense layer of substance when immersion for 7 d. More and more particles with a cluster-like structure appear on the surface of bioceramics and become dense as the immersion duration increases. In Figs. 11(d) and 11(e), cluster-like apatite continues to grow on the surface of ceramics and gradually densifies.

According to some previous studies^[49–51], ion

The *in-vitro* bioactivity of bioceramic scaffolds is evaluated by immersing them in SBF solution at different durations. Fig. 10 shows the XRD patterns and FTIR spectra of surface of bioceramics after immersing for different durations. Clearly, all scaffolds have the similar phase components (i.e., $\text{Ca}_5(\text{PO}_4)_3\text{OH}$, $\text{Ca}_3(\text{PO}_4)_2$, and $\text{Ca}_2\text{MgSi}_2\text{O}_7$). However, some absorptions at the wavenumbers of 873 cm^{-1} , 1418 and 1450 cm^{-1} appear, which correspond to carbonate (ν_3 stretching at 1417 cm^{-1} and 1455 cm^{-1} ; ν_3 bending at 875 cm^{-1})^[46–47]. According to Padilla et al^[48], carbonated hydroxyapatite can be detected by FTIR, showing a good *in-vitro* bioactivity of bioceramics.

exchange during bioceramics and SBF solution at the initial stage of immersion leads to an alkaline environment and the process of apatite deposition. Si—OH group is formed (see Eqs. (4) and (5)), which produces the silica gel layer (see Fig. 11(c)). Si—OH group is dissociated into negatively charged units, which attracts Ca^{2+} and PO_4^{2-} in turn to form amorphous calcium phosphate rapidly due to the alkaline environment.

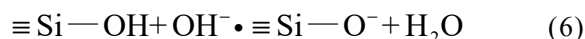
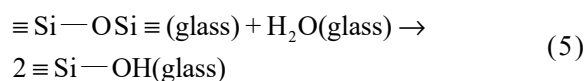
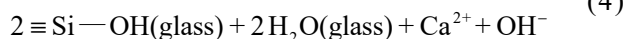
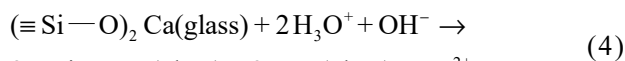


Fig. 12 shows the top-view of bioceramic scaffolds with bone shape. Clearly, the uniform structure (i.e., a

porosity of 70%) and hierarchical gyroid bioceramic scaffolds with a bone geometry is fabricated. The hierarchical gyroid scaffold has the same external characters and a substantial increase in a maximum load. In Fig. 12(b), the maximum load of the scaffold with a bone geometry is approximately 8-fold higher than that of the uniform structure. Therefore, the

complex shape may enlarge the advantages of this kind of hierarchical gyroid structure, compared with a cylinder. This also indicates that the additive manufacturing technology can customize the corresponding gradient structure bone scaffold for the bone defect site, and can apply the gradient structure to the actual prepared bone scaffold.

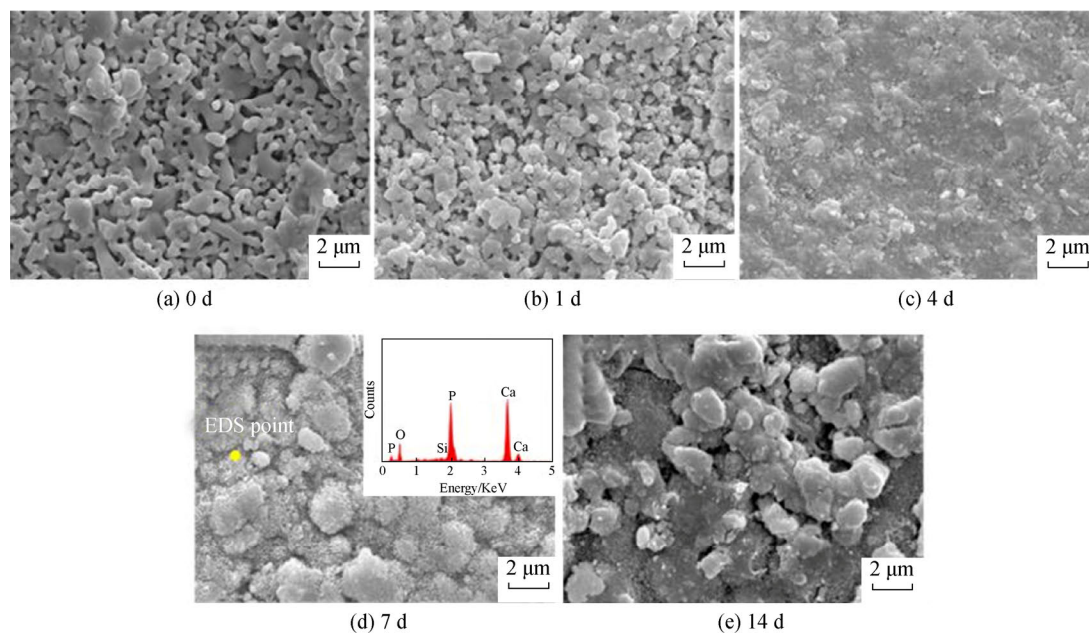


Fig. 11 SEM images and EDS spectra for surface micromorphology of bioceramic scaffolds for different immersion durations

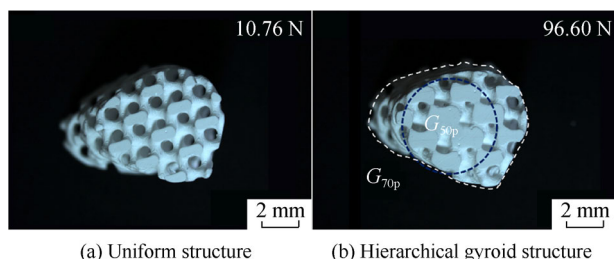


Fig. 12 Top-view of bioceramic scaffolds with bone shape

4 Conclusions

The hierarchical gyroid HA & AK scaffolds with radially partitioned porosities from 50% (inside) to 70% (outside) were designed to realize functional partition. The DLP-printed scaffolds could correspond to models and have a network of interconnected pores. The elastic modulus and compressive strength of scaffolds increased as the transition diameters increased. The compressive strength of G75 (*i.e.*, 2.15 MPa) was increased by 1.5-fold, compared to G0 (*i.e.*, 0.87 MPa),

which was suitable for cancellous bone repair. For G75, after immersing in Tris-HCL solution for 1 d, interconnected micropore and ion-exchange between $\text{Ca}_2\text{MgSi}_2\text{O}_7$ and solution both resulted in a rapid degradation rate of 5.73%, which also decreased the compressive strength of scaffolds slightly. The degradation speed slowed down, and the mass and the compressive strength of scaffolds increased at 14 d as the immersion duration further increased due to apatite deposition. The composite bioceramics had a good *in-vitro* bioactivity to repair bone defects. Finally, the hierarchical gyroid with bone geometries was fabricated, and the maximum force was 8-fold higher than that of the uniform structure. This work could provide hierarchical bioceramic implants with functional zoning for bone tissue engineering, having improved mechanical properties, superior bone repair ability, and degradation ability prepared by DLP technology.

References:

- [1] ZHOU J G, XIONG Z K, LIU M, et al. Creation of bony microenvironment with extracellular matrix doped-bioactive ceramics to enhance osteoblast behavior and delivery of aspartic acid-modified BMP-2 peptides[J]. *Int J Nanomedicine*, 2020, 15: 8465–8478.
- [2] CHIU Y C, SHIE M Y, LIN Y H, et al. Effect of strontium substitution on the physicochemical properties and bone regeneration potential of 3D printed calcium silicate scaffolds[J]. *Int J Mol Sci*, 2019, 20(11): 2729.
- [3] LIN S H, YANG G Z, JIANG F, et al. Bone regeneration: A magnesium-enriched 3D culture system that mimics the bone development microenvironment for vascularized bone regeneration (adv. sci. 12/2019)[J]. *Adv Sci*, 2019, 6(12): 1900209.
- [4] DING J X, WANG H, CUI X, et al. Recent development on borosilicate bioactive glass biomaterials [J]. *J Chin Ceram Soc*, 2022, 50(4): 1074–1084.
- [5] ALARÇIN E, LEE T Y, KARUTHEDOM S, et al. Injectable shear-thinning hydrogels for delivering osteogenic and angiogenic cells and growth factors[J]. *Biomater Sci*, 2018, 6(6): 1604–1615.
- [6] SPICER P P, KRETLOW J D, YOUNG S, et al. Evaluation of bone regeneration using the rat critical size calvarial defect[J]. *Nat Protoc*, 2012, 7(10): 1918–1929.
- [7] MA L, YU Y J, LIU H X, et al. Berberine-releasing electrospun scaffold induces osteogenic differentiation of DPSCs and accelerates bone repair[J]. *Sci Rep*, 2021, 11(1): 1027.
- [8] WEI J, SUN X Q, HOU B X. Evaluation of silk fibroin-RGD-stem cell factor scaffold effect on adhesion, migration, and proliferation of stem cells of apical papilla[J]. *Stem Cells Int*, 2021, 2021: 6612324.
- [9] LEE D J, DIACHINA S, LEE Y T, et al. Decellularized bone matrix grafts for calvaria regeneration[J]. *J Tissue Eng*, 2016, 7: 2041731416680306.
- [10] ZHANG Y M, WANG C E, JIANG W, et al. Influence of stage cooling method on pore architecture of biomimetic alginate scaffolds[J]. *Sci Rep*, 2017, 7(1): 16150.
- [11] XIAO W, ZAEEM M A, LI G D, et al. Tough and strong porous bioactive glass-PLA composites for structural bone repair[J]. *J Mater Sci*, 2017, 52(15): 9039–9054.
- [12] JIANG S M, LYU C, ZHAO P, et al. Cryoprotectant enables structural control of porous scaffolds for exploration of cellular mechano-responsiveness in 3D[J]. *Nat Commun*, 2019, 10(1): 3491.
- [13] BRAY L J, SECKER C, MUREKATETE B, et al. Three-dimensional *in vitro* hydro-and cryogel-based cell-culture models for the study of breast-cancer metastasis to bone[J]. *Cancers*, 2018, 10(9): 292.
- [14] KIM J W, HAN Y S, LEE H M, et al. Effect of morphological characteristics and biomineralization of 3D-printed gelatin/hyaluronic acid/hydroxyapatite composite scaffolds on bone tissue regeneration[J]. *Int J Mol Sci*, 2021, 22(13): 6794.
- [15] TARAFDER S, DAVIES N M, BANDYOPADHYAY A, et al. 3D printed tricalcium phosphate bone tissue engineering scaffolds: Effect of SrO and MgO doping on *in vivo* osteogenesis in a rat distal femoral defect model[J]. *Biomater Sci*, 2013, 1(12): 1250–1259.
- [16] MEMARIAN P, SARTOR F, BERNARDO E, et al. Osteogenic properties of 3D-printed silica-carbon-calcite composite scaffolds: Novel approach for personalized bone tissue regeneration[J]. *Int J Mol Sci*, 2021, 22(2): 475.
- [17] PIERANTOZZI D, SCALZONE A, JINDAL S, et al. 3D printed Sr-containing composite scaffolds: Effect of structural design and material formulation towards new strategies for bone tissue engineering[J]. *Compos Sci Technol* 2020, 191: 108069.
- [18] TELLIS B C, SZIVEK J A, BLISS C L, et al. Trabecular scaffolds created using micro CT guided fused deposition modeling[J]. *Mater Sci Eng C Mater Biol Appl*, 2009, 28(1): 171–178.
- [19] HE F P, YE J D. Bi-layered calcium phosphate cement-based composite scaffold mimicking natural bone structure[J]. *Sci Technol Adv Mater*, 2013, 14(4): 045010.
- [20] HUANG L, HUANG J W, SHAO H L, et al. Silk scaffolds with gradient pore structure and improved cell infiltration performance[J]. *Mater Sci Eng C Mater Biol Appl*, 2019, 94: 179–189.
- [21] ZHANG Q, LU H X, KAWAZOE N, et al. Preparation of collagen porous scaffolds with a gradient pore size structure using ice particulates[J]. *Mater Lett*, 2013, 107: 280–283.
- [22] BAI H, WANG D, DELATTRE B, et al. Biomimetic gradient scaffold from ice-templating for self-seeding of cells with capillary effect[J]. *Acta Biomater*, 2015, 20: 113–119.
- [23] CHEN Y W, ZHANG J M, LIU X, et al. Noninvasive *in vivo* 3D bioprinting[J]. *Sci Adv*, 2020, 6(23): eaba7406.
- [24] XU X Q, FAN J X, NIU S X, et al. Strengthening of silica ceramic cores fabricated by 3D printing [J]. *J Chin Ceram Soc*, 2022, 50(9): 2422–2429.
- [25] LI Y, JAHR H, PAVANRAM P, et al. Additively manufactured functionally graded biodegradable porous iron[J]. *Acta Biomater*, 2019, 96: 646–661.
- [26] DI LUCA A, LONGONI A, CRISCENTI G, et al. Toward mimicking the bone structure: Design of novel hierarchical scaffolds with a tailored radial porosity gradient[J]. *Biofabrication*, 2016, 8(4): 045007.
- [27] LINDNER M, BERGMANN C, TELLE R, et al. Calcium phosphate scaffolds mimicking the gradient architecture of native long bones[J]. *J Biomed Mater Res A*, 2014, 102(10): 3677–3684.
- [28] LIAO B, XIA R F, LI W, et al. 3D-printed Ti₆Al₄V scaffolds with graded triply periodic minimal surface structure for bone tissue engineering[J]. *J Mater Eng Perform*, 2021, 30(7): 4993–5004.
- [29] SHAN Y B, BAI Y, YANG S, et al. 3D-printed strontium-incorporated β -TCP bioceramic triply periodic minimal surface scaffolds with simultaneous high porosity, enhanced strength, and excellent bioactivity[J]. *J Adv Ceram*, 2023, 12(9): 1671–1684.
- [30] ZHANG X Q, ZHANG K Q, ZHANG B, et al. Mechanical properties of additively-manufactured cellular ceramic structures: A comprehensive study[J]. *J Adv Ceram*, 2022, 11(12): 1918–1931.
- [31] LIM H K, HONG S J, BYEON S J, et al. 3D-printed ceramic bone scaffolds with variable pore architectures[J]. *Int J Mol Sci*, 2020, 21(18): 6942.
- [32] HUGHES E A, PARKES A, WILLIAMS R L, et al. Formulation of a covalently bonded hydroxyapatite and poly (ether ether ketone) composite[J]. *J Tissue Eng*, 2018, 9: 2041731418815570.
- [33] TARAFDER S, BOSE S. Polycaprolactone-coated 3D printed tricalcium phosphate scaffolds for bone tissue engineering: *in vitro* alendronate release behavior and local delivery effect on *in vivo* osteogenesis[J]. *ACS Appl Mater Interfaces*, 2014, 6(13): 9955–9965.
- [34] LEWANDROWSKI K U, GRESSER J D, BONDRE S, et al. Developing porosity of poly(propylene glycol-co-fumaric acid) bone graft substitutes and the effect on osteointegration: A preliminary histology study in rats[J]. *J Biomater Sci Polym Ed*, 2000, 11(8): 879–889.

- [35] KAPFER S C, HYDE S T, MECKE K, et al. Minimal surface scaffold designs for tissue engineering[J]. *Biomaterials*, 2011, 32(29): 6875–6882.
- [36] YANG N, QUAN Z, ZHANG D W, et al. Multi-morphology transition hybridization CAD design of minimal surface porous structures for use in tissue engineering[J]. *Comput Aided Des*, 2014, 56: 11–21.
- [37] YANG N, TIAN Y L, ZHANG D W. Novel real function based method to construct heterogeneous porous scaffolds and additive manufacturing for use in medical engineering[J]. *Med Eng Phys*, 2015, 37(11): 1037–1046.
- [38] HUA S B, YUAN X, WU J M, et al. Digital light processing porous TPMS structural HA & akermanite bioceramics with optimized performance for cancellous bone repair[J]. *Ceram Int*, 2022, 48(3): 3020–3029.
- [39] KOKUBO T, KUSHITANI H, SAKKA S, et al. Solutions able to reproduce *in vivo* surface-structure changes in bioactive glass–ceramic A-W[J]. *J Biomed Mater Res*, 1990, 24(6): 721–734.
- [40] LIN R C, DENG C J, LI X X, et al. Copper-incorporated bioactive glass-ceramics inducing anti-inflammatory phenotype and regeneration of cartilage/bone interface[J]. *Theranostics*, 2019, 9(21): 6300–6313.
- [41] FU S Y, LIU W, LIU S W, et al. 3D printed porous β -Ca₂SiO₄ scaffolds derived from preceramic resin and their physicochemical and biological properties[J]. *Sci Technol Adv Mater*, 2018, 19(1): 495–506.
- [42] CHARTIER T, CHAPUT C, DOREAU F, et al. Stereolithography of structural complex ceramic parts[J]. *J Mater Sci*, 2002, 37(15): 3141–3147.
- [43] PUÉRTOLAS J A, VADILLO J L, SÁNCHEZ-SALCEDO S, et al. Compression behaviour of biphasic calcium phosphate and biphasic calcium phosphate-agarose scaffolds for bone regeneration[J]. *Acta Biomater*, 2011, 7(2): 841–847.
- [44] LIU X, RAHAMAN M N, DAY D E. Conversion of melt-derived microfibrillar borate (13-93B3) and silicate (45S5) bioactive glass in a simulated body fluid[J]. *J Mater Sci Mater Med*, 2013, 24(3): 583–595.
- [45] KOKUBO T, KIM H M, KAWASHITA M. Novel bioactive materials with different mechanical properties[J]. *Biomaterials*, 2003, 24(13): 2161–2175.
- [46] ROMEIS S, HOPPE A, EISERMANN C, et al. Enhancing *in vitro* bioactivity of melt-derived 45S5 bioglass® by comminution in a stirred media mill[J]. *J Am Ceram Soc*, 2014, 97(1): 150–156.
- [47] KALINKINA E V, KALINKIN A M, FORSLING W, et al. Sorption of atmospheric carbon dioxide and structural changes of Ca and Mg silicate minerals during grinding[J]. *Int J Miner Process*, 2001, 61(4): 273–288.
- [48] PADILLA S, ROMAN J, SANCHEZSALCEDO S, et al. Hydroxyapatite/SiO₂–CaO–P₂O₅ glass materials: *in vitro* bioactivity and biocompatibility[J]. *Acta Biomater*, 2006, 2(3): 331–342.
- [49] CHEN Q Z, REZWAN K, FRANÇON V, et al. Surface functionalization of Bioglass-derived porous scaffolds[J]. *Acta Biomater*, 2007, 3(4): 551–562.
- [50] MAGALLANES-PERDOMO M, MEILLE S, CHENAL J M, et al. Bioactivity modulation of Bioglass® powder by thermal treatment[J]. *J Eur Ceram Soc*, 2012, 32(11): 2765–2775.
- [51] TAKADAMA H, KIM H M, KOKUBO T, et al. Mechanism of biomineralization of apatite on a sodium silicate glass: TEM–EDX study *in vitro*[J]. *Chem Mater*, 2001, 13(3): 1108–1113.

3D Printing of Hierarchical Gyroid Hydroxyapatite-Akermanite Scaffolds with Improved Compressive Strength

HUA Shuaibin^{1,2}, PENG Chang^{1,2,3}, CHENG Lijin⁴, WU Jiamin^{1,2,3}, ZHANG Xiaoyan⁵, WANG Xiumei⁶, SHI Yusheng^{1,2}

(1. State Key Laboratory of Materials Processing and Die & Mould Technology, School of Materials Science and Engineering, Huazhong University of Science and Technology, Wuhan, 430074, China; 2. Engineering Research Center of Ceramic Materials for Additive Manufacturing, Ministry of Education, Wuhan, 430074, China; 3. Wenzhou Advanced Manufacturing Institute of HUST, Wenzhou, Zhejiang, 325035, China; 4. School of Mechanical Engineering, Hebei University of Technology, Tianjin 300401, China; 5. Institute for Advanced Materials and Technology, University of Science and Technology Beijing, Beijing, 100083, China; 6. State Key Laboratory of New Ceramic Materials, Tsinghua University, Beijing 100084, China)

Introduction It is necessary for an ideal bioceramic scaffold to have a suitable structure. The structure can affect the mechanical properties of the scaffold (*i.e.*, elastic modulus and compressive strength) and the biological properties of the scaffold (*i.e.*, degradability and cell growth rate). Lattice structure is a kind of periodic porous structure, which has some advantages of light weight and high strength, and is widely used in the preparation of bioceramic scaffolds. For the structure of the scaffold, high porosity and large pore size are important for bone growth, bone integration and promoting good mechanical interlocking between neighboring bones and the scaffold. However, scaffolds with a high porosity often lack mechanical strength. In addition, different parts of the bone have different structural requirements. In this paper, scaffolds with a non-uniform structure or a hierarchical structure were designed, with loose and porous exterior to facilitate cell adhesion, osteogenic differentiation and vascularization as well as relatively dense interior to provide sufficient mechanical support for bone repair.

Methods In this work, composite ceramics scaffolds with 10% akermanite content were prepared by DLP technology. The scaffold had a high porosity outside to promote the growth of bone tissue, and a low porosity inside to withstand external forces. The compressive strength, fracture form, *in-vitro* degradation performance and bioactivity of graded bioceramic scaffolds were investigated. The models of scaffolds were imported into the DLP printer with a 405 nm light. The samples were printed with the intensity of 8 mJ/cm² and a layer thickness of 50 μm. Finally, the ceramic samples were sintered at 1100 °C. The degradability of the

hierarchical gyroid bioceramic scaffolds was evaluated through immersion in Tris-HCl solution and SBF solution at a ratio of 200 mL/g. The bioactivity of bioceramic was obtained *via* immersing them in SBF solution for two weeks. The concentrations of calcium, phosphate, silicon, and magnesium ions in the soaking solution were determined by an inductively coupled plasma optical emission spectrometer.

Results and discussion In this work, a hierarchical Gyroid structure HA-AK10 scaffold (sintered at 1100 °C) with a radial internal porosity of 50% and an external porosity of 70% is prepared, and the influence of structural form on the compressive strength and degradation performance of the scaffold is investigated. The biological activity of the bioceramics *in vitro* is also verified. The mechanical simulation results show that the stress distribution corresponds to the porosity distribution of the structure, and the low porosity is larger and the overall stress concentration phenomenon does not appear. After soaking in SBF solution, Si—OH is firstly formed on the surface of bioceramics, and then silicon gel layer is produced due to the presence of calcium and silicon ions. The silicon gel layer is dissociated into negatively charged groups under alkaline environment secondary adsorption of calcium ions and phosphate ions, forming amorphous calcium phosphate, and finally amorphous calcium phosphate crystals and adsorption of carbonate ions, forming carbonate hydroxyapatite. This indicates that the composite bioceramics have a good biological activity *in-vitro* and can provide a good environment for the growth of bone cells. A hierarchical Gyroid ceramic scaffold with a bone geometry is prepared *via* applying the hierarchical structure to the bone contour scaffold. The maximum load capacity of the hierarchical Gyroid ceramic scaffold is 8 times that of the uniform structure.

Conclusions The hierarchical structure scaffold designed had good overall compressive performance, good degradation performance, and still maintained a good mechanical stability during degradation. In addition, *in-vitro* biological experimental results showed that the surface graded composite scaffold could have a good *in-vitro* biological activity and provide a good environment for bone cells. Compared to the heterosexual structure, the graded scaffold had greater mechanical properties.

Keywords bioceramic scaffolds; hierarchical gyroid structure; compressive strength; bioactivity; digital light processing