Research Article

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Fused deposition modeling of poly(ether ether ketone) scaffolds

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Abstract: In this paper, poly(ether ether ketone) (PEEK) scaffold was manufactured using the fused deposition modeling (FDM) technology with a modified platform. The effect of processing parameters of FDM on the porosity and compressive strength of PEEK scaffold with uniform pores (0.8 mm of diameter) was optimized through Taguchi methodology. With the determined parameters, four kinds of PEEK scaffolds with gradient pores (0.4–0.8 mm, 0.6–1.0 mm, 0.8–1.2 mm, and 1.2–2.0 mm) were manufactured. The scaffolds were investigated using scanning electron microscopy. The results showed that the pores of scaffolds were interconnected with rough surface, which can allow the attachment, migration, and differentiation of cells for bone forming. The tensile strength, compressive max strength, and compressive yield strength of scaffolds were between 18 and 35 MPa, 197.83 and 370.42 MPa, and 26 and 36 MPa, respectively. The mechanical properties of the scaffolds can satisfy the loading requirements of human bones. Therefore, the PEEK scaffolds have a potential to be used in tissue engineering as implants.

Keywords: fused deposition modeling, poly(ether ether ketone), scaffolds, mechanical properties

1 Introduction

Today, the majority of implants for bone regeneration are mainly made from three kinds of materials: ceramics, titanium (Ti), and poly(ether ether ketone) (PEEK) [1]. Bioactive ceramics, for example hydroxyapatite, can integrate spontaneously with human bones but were used rarely because of their high modulus and high brittleness [2]. Ti and Ti alloys have been reported in massive clinical studies [3], which easily caused two major issues such as stress shielding and local inflammation [4]. It seems that the most suitable candidate is PEEK, which has a number of characteristics making it to stand out. PEEK has an elastic modulus of 3–4 GPa, which is closer to that of human cortical bone (14 GPa). Its modulus can help PEEK to reduce or remove the occurrence of stress shielding and bone resorption [1]. Unlike the metal implants, PEEK will not create artifacts in medical radiographic evaluation, such as X-ray and CT [5]. PEEK is a high temperature-resistant plastic with a melting point around 343°C. It is thermally stable and will not degrade at the sterilization temperature [6].

A bone implant should use bioactive material, possesses suitable elastic modulus, and also needs to be a porous scaffold with interconnecting pores providing for cell attaching and tissue in-growth [7]. In recent years, additive manufacturing (AM) has developed as a promising technology in the aspect of customizing bone scaffolds for bone reconstruction. There are two types of AM methods to process PEEK, such as selective laser sintering (SLS) and fused deposition modeling (FDM). Singh et al. [8] reviewed the biomedical applications of SLS on PEEK and concluded the merits and shortcomings of SLS. PEEK is a kind of semi-crystalline thermoplastic, which needs to be preheated to a powder-bed temperature close to its melting point [9]. Preheating is essential for keeping the dimensional stability of the SLS parts [10]. During the SLS procedure, the support powders in a sealed chamber were easy aging under a high temperature for long time [11,12]. The aging of powders was

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induced by thermal oxidation and had no way to be improved [13]. Even though those powders could be reused, it will compromise on mechanical properties [14]. Because of the limitations of SLS of PEEK, researchers shifted their focus onto FDM of PEEK.

In 2013, Valantan *et al.* [15] first used a custom-made FDM machine to process PEEK. However, the products obtained had defects including warpage, delamination, and bubbles. After that, Vaezi and Yang [16] 3D printed PEEK structures successfully using an extrusion AM setup. However, there was a reduction in mechanical strength because of the air gaps between the infill lines and inside the filaments. Therefore, to improve the quality of FDM on the manufacturing of PEEK parts, some studies have been carried out to investigate the relationship between processing parameters and the mechanical properties. Rahman *et al.* [17], Wu *et al.* [18], and Arif *et al.* [19] investigated the effect of raster orientation on mechanical properties of FDM PEEK and concluded that samples at 0° orientation showed stronger tensile properties. Zalaznik *et al.* [20], Yang *et al.* [21], and Wang *et al.* [22] focused on the effect of FDM processing temperature on the mechanical properties and the crystallinity of PEEK. Xiaoyong *et al.* [23] adjusted the printing temperature and filling ratio to improve the mechanical properties of FDM PEEK. Zhao *et al.* [24] improved the mechanical strength of PEEK through controlling the nozzle temperature, platform temperature, and filament diameter of FDM. Ding *et al.* [25] analyzed the effect of the nozzle temperature and raster orientation on the mechanical properties of FDM PEEK. Basgul *et al.* [26] and Geng *et al.* [27] gave the effect of printing speed on the PEEK parts manufactured by FDM. Deng *et al.* [28] comprehensively investigated the relationship between the printing speed, layer thickness, and printing temperature on the tensile properties of PEEK. Except those studies, the combination of computer-aided methods and processing parameters were adopted to improve the quality of FDM PEEK, including finite element analysis [29] and fuzzy proportion-integration-differentiation (PID) method [30].

All these studies have made a significant contribution to the effects of FDM processing parameters on the properties of PEEK. However, the PEEK parts in these studies are not the porous structure, which is the key for the cell attachment, proliferation, migration, and differentiation [31]. Therefore, the effect of the FDM processing parameter on the porosity of scaffold should be evaluated for getting an optimal application in tissue engineering. This study was about to carry out the processing of PEEK scaffold. The purposes were as follows: investigating the effect of FDM parameters on the

mechanical properties of PEEK scaffolds with uniform pores using the Taguchi methodology; evaluating the relationship between the different gradient pores and the mechanical properties with the optimal processing parameters; and characterizing the morphology and the tensile fracture surface of PEEK scaffolds with gradient pores.

2 Materials and experiments

The PEEK filament was a medical-grade polymer, purchased from Jilin Zhongyan, China. Its properties provided by the manufacturer are presented in Table 1. The filament was applied on a high temperature FDM setup (CreatBot F430, Henan, China). The nozzle temperature of this FDM machine was recommended between 390 and 430°C, and the platform can reach and keep a stable temperature at 100°C. The nozzle diameter was chosen as 0.3 mm. With the filament and FDM machine, specimens prepared for tensile and compressive testing were manufactured.

For each series of Taguchi experiment, three compression scaffolds were manufactured using FDM machine. As shown in Figure 1a, the scaffold was a porous cylinder with a dimension of 10 × 10 mm. The pores were interconnected with a diameter of 0.8 mm. For further experiment, three dumbbell scaffolds with a dimension of 63.5 × 9.53 × 3.2 mm and four cylinder compression scaffolds with a diameter of 10 mm and height of 15 mm were prepared. As shown in Figure 1b, four kinds of interconnected gradient pores (a and b: 0.4–0.8 mm, 0.6–1.0 mm, 0.8–1.2 mm, and 1.2–2.0 mm) were set in those scaffolds and increased from outer side to center.

Considering that the material PEEK is hard to adhere onto the platform of the FDM machine, three kinds of platform modifications were tried, as shown in Figure 2. Figure 2a shows the platform provided by the manufacturer, which was made from carbon fiber/pyroceram composite. The test results showed that PEEK parts

Table 1: Some properties of molded PEEK

Properties	PEEK
Density (g/cm ³)	1.3
Glass-transition temperature (°C)	143
Melting temperature (°C)	343
Tensile strength (MPa)	100
Flexural strength (MPa)	170
Compressive strength (MPa)	125

Figure 1: The porous scaffolds with (a) uniform pores, (b) gradient pores, and (c) section of (a).

Figure 2: The modification of FDM platform: (a) a platform proved by manufacturer, (b) spreading a glue evenly on the platform, (c) pasting a polycarbonate (PC) plate on the platform, and (d) pasting a PCB plate on the platform.

moved strongly during the FDM processing, indicating that PEEK hardly adhered onto this material. Therefore, the following three methods were adopted: spreading a glue evenly on the platform (Figure 2b), pasting a polycarbonate (PC) plate on the platform (Figure 2c), and pasting a printed circuit board (PCB) on the platform (Figure 2d). The backside holes on PCB were drilled to stepped ones. These test results showed that the glue was able to stay the PEEK parts during the processing. However, the spreading evenness of the glue was difficult to control, resulting in a certain slightly moving of the PEEK parts during the processing. The PCB perfectly retained the PEEK parts on it. However, when removing the PEEK from the PCB, deformation of PCB and breaks on stepped holes occurred. Finally, the PC plate withstood the test by sticking the PEEK parts onto it and being used repeatedly, which was chosen to further develop the FDM of PEEK.

The Taguchi methodology was used to determine the relationship between FDM processing parameters and the properties of scaffolds with uniform pores. The nozzle temperature (T), the printing speed (V), and the layer thickness (H) were chosen as the studied factors, which were assigned to three levels, respectively, as presented in Table 2. The array L_9 (3^3) was selected, as presented in Table 3. The three columns were assigned to T , V , and H in sequence. The porosity of the scaffolds and

compressive properties were selected as the outputs. Nine series of experiments were carried out according to the array. Based on the average analysis (ANOVA) [32], the experimental results were treated.

Range analysis was carried out with the porosity and compressive strength for obtaining the optimized processing parameters. K_{ij} represents the average of the experimental results, and R_{ij} denotes the range and can be calculated by equation (1):

$$R_{ij} = \max(K_{ij}) - \min(K_{ij}) \quad i, j = 1, 2, 3, \quad (1)$$

where i is the level and j is the sequence of the three factors.

The porosity of the scaffold can be obtained by equation (2):

$$\text{Porosity} = 1 - \frac{\rho_0}{\rho_{\text{PEEK}}}, \quad (2)$$

Table 2: Arrangement of the levels to the factors

Level (i)	Nozzle temperature (T , °C)	Printing speed (V , mm/s)	Layer thickness (H , mm)
1	390	10	0.8
2	410	20	1.0
3	430	30	1.2

where ρ_{PEEK} is the theoretical densities (g/cm^3) of PEEK filament and equals to 1.3 g/cm^3 provided by the supplier; ρ_0 is the apparent density calculated through the equation

$$\rho_0 = m_0/V_0, \quad (3)$$

where m_0 is the scaffold mass (g) obtained using a scale with accuracy of 0.001 g, and V_0 is the volume (mm^3) of sample measured by a Vernier caliper.

The compressive properties of the scaffolds were tested using a universal testing machine (Model 8800, Instron, Canton, MA). The crosshead speed and the preload were set as 0.5 mm/min and 0.1 N, respectively. Another universal testing machine (WDW, 20KN, Jinan Zhongbiao, China) was used to carry out the tensile properties with a preload of 0.1 N and a testing rate of 0.05 mm/s. The average values of the testing strength and strain for each sample were obtained through four measurements.

The morphology of the manufacturing surface and the fractural surface was observed. The test was carried out using a scanning electron microscopy (SEM, VEGA3 TESCAN). Before testing, all the scaffolds were gold coated for 3 min.

3 Results and discussions

3.1 Taguchi experiment of scaffolds with uniform pores

Table 3 presents the results of the Taguchi experiment. The porosity of the scaffolds varies from 47 to 59% and the compressive strength was in the range of 274–421 MPa, showing that the parameters had an important effect on the porosity and mechanical properties of the scaffolds. The range analysis of the results is presented in Table 4 to further determine the optimized processing parameters. For compressive strength, the optimum combination was T3V1H3, which was contributing to the nozzle temperature of 430°C , the printing speed of 10 mm/s, and the layer thickness of 0.08 mm. On the contrary, the optimal assembly for porosity was T1V3H2, which was corresponding to the nozzle temperature of 390°C , the printing speed of 30 mm/s, and the layer thickness of 0.12 mm. For a scaffold applied in tissue engineering, larger strength means stronger anti-bearing

Table 3: The results of Taguchi experiment

Temperature ($^\circ\text{C}$)	Printing speed (mm/s)	Layer thickness (mm)	Porosity (%)	Compressive strength (MPa)
390	10	0.12	49.72 ± 0.77	325.25 ± 2.19
390	20	0.08	51.28 ± 0.7	336.85 ± 1.83
390	30	0.1	58.67 ± 0.39	274.59 ± 6.56
410	10	0.08	48.81 ± 0.1	381.89 ± 0.94
410	20	0.1	49.71 ± 0.37	353.92 ± 0.22
410	30	0.12	54.42 ± 0.76	363.24 ± 0.39
430	10	0.1	47.72 ± 0.01	421.48 ± 5.72
430	20	0.12	51.92 ± 0.28	367.02 ± 5.57
430	30	0.08	47.27 ± 0.92	402.45 ± 6.28

Table 4: The range analysis of the compressive strength and porosity

Range	Compressive strength (MPa)			Porosity (%)		
	<i>T</i>	<i>V</i>	<i>H</i>	<i>T</i>	<i>V</i>	<i>H</i>
K_{1j}	312.23	376.21	373.73	53.22	48.75	49.12
K_{2j}	366.35	352.60	350.00	50.98	50.97	52.03
K_{3j}	396.98	346.76	351.84	48.97	53.45	52.02
<i>R</i>	84.75	29.45	23.73	4.25	4.7	2.91
Optimum levels	T3	V1	H3	T1	V3	H2
Optimum assembly		T3V1H3			T1V3H2	
Order of priority		TVH			VTH	

capacity [33], and higher porosity is benefit to the bone ingrowth [34]. Therefore, here a compromise was needed.

From Table 4, it can be seen that higher temperature was benefit to the strength and was able to decrease the porosity. This result was similar to that in other literatures [21,25,30]. Higher temperature provided more heat to make PEEK to melt well and gave the molecular chains more energy to rearrange. The micro-voids inside the part can be decreased in higher temperature, resulting in a higher strength and density. Meanwhile, higher temperature provided longer time for PEEK to crystallize because of a larger difference with the ambient temperature. Literature [21] reported that the increase in crystallinity improved the yield strength of PEEK but decreased its toughness. Therefore, the compressive strength of PEEK in this study should be enhanced in higher nozzle temperature. It can also be proved by the picture of the FDM scaffolds in Figure 3. Scaffold in Figure 3b showed brighter surface than scaffold in Figure 3a. Polymer parts with brighter surface had higher crystallinity than those with darker surface. Therefore, the scaffold in Figure 3b possessed higher strength (367.02 MPa) than scaffold in Figure 3a (336.85 MPa).

Increasing the printing speed had a negative effect on the compressive strength and density of PEEK. The effect of printing speed on the strength of PEEK was similar to that in the literature [30]. When PEEK melts were squeezed quickly, the molecular of PEEK had insufficient time to unfold and orient, weakening the bonding strength between two adjacent printing lines and layers. At the same time, the PEEK filaments absorbed less energy when being squeezed from nozzle at the higher speed, lowering the crystallinity of PEEK. Therefore, the scaffold in Figure 3c, which was manufactured with higher printing speed (30 mm/s) and lower nozzle temperature (390°C), possessed dark and rough surface [35]. The result indicated that the printing speed of 30 mm/s might too fast for ensuring the quality of the PEEK scaffold.

Figure 3: The PEEK scaffold in different processing condition (the nozzle temperature, the printing speed, and the layer thickness): (a) 390°C, 20 mm/s, 0.08 mm; (b) 430°C, 20 mm/s, 0.12 mm; (c) 390°C, 30 mm/s, 0.1 mm; and (d) 430°C, 10 mm/s, 0.1 mm.

The effect of layer thickness on the compressive strength and the porosity was the weakest among the three factors. Although there was almost no difference at the layer thickness 0.1 and 0.12 mm for the average compressive strength and porosity (350 MPa and 52%), the gap was still big between 0.08 and 0.1 mm (373.73 MPa and 49.12%). When manufacturing with smaller layer thickness, the redundant heat released from the printing layer can be absorbed by the former layer, resulting in a stronger bond between two layers. However, when the layer thickness was very small, there was no enough room for the redundant melting polymers, which will be aggressive under the situation of higher nozzle temperature and lower printing speed. Therefore, those superfluous melts flowed to other room, resulting in the congested pores in the scaffold, as shown in Figure 3d. The blocking pores would not be able to provide ways for bone cells to ingrowth.

In a conclusion, although higher temperature and lower speed were benefit to the crystalline of PEEK, they prevented the forming of micro pores. Micro pores were the key for bone cells to ingrowth and migrate. Therefore, a moderate temperature and printing speed should be chosen. The layer thickness had the weakest effect on the strength and the porosity, so a modest choice for it should be fine. As a result, the optimum processing parameters were determined as: the nozzle temperature of 410°C, the printing speed of 20 mm/s, and the layer thickness of 0.1 mm. With the optimum processing parameters, the compression and tensile sample were manufactured and tested. The sample was designed as porous scaffold with uniform pores of 0.8 mm in diameter, as shown in Figure 4. Figure 4a showed that most of the pores in scaffold were exact 0.8 mm in diameter, indicating that the dimension of scaffold can be controlled during the FDM processing. Some pores were a little less than 0.8 mm, which might because of the molecular swell of PEEK melts (Figure 4b).

Figure 4: The surface morphology of (a) a scaffold with uniform pores and (b) the enlarger of the one of the pores.

There were many micro-pores ($5\text{--}40\text{ }\mu\text{m}$) on the surface of scaffold (red rectangle), contributing to the air gap during the process. Literatures [36,37] showed that pores in size of $10\text{--}75\text{ }\mu\text{m}$ allowed the fibrous tissue to penetrate into. Therefore, the PEEK scaffold with micro pores in size of $5\text{--}40\text{ }\mu\text{m}$ was benefit to the penetration of fibrous tissue.

3.2 Analysis of the compression procedure of FDM PEEK scaffold

Section 3.1 proved the importance of the FDM processing parameters, which not only affected the morphology, porosity, and mechanical properties, but also decided the success use of a scaffold. Figure 5 shows a failed example of compression of PEEK scaffold. The compression procedure of this example scaffold included five stages as follows: elastic, yield, partial failure, yield, and densification. During the first stage, the scaffold (picture 1), along with its pores, decreased in height and increased in parallel direction under the downward load. In this period, the pores deformed without collapse and can be recovered to its original shape. After that, the scaffold came into the first yield phase because of a weak point (red arrow), which resulted in a collapse (picture 2). This weak point caused the scaffold to distort, resulting in a compressive deformation on the right side and a tensile deformation on the left side of the scaffold (picture 3). When the beams around the tensile area were broken (red rectangle), the second stage was finished (picture 4). At this stage, the strength increased slowly from 30 to 38.39 MPa. Then the crack further propagated to lower the strength (picture 5), and this stage was called partial

failure. When the cracks stopped to propagate and disappeared because of the compression, the procedure went to the second yield phase (picture 6). In this stage, all the pores were compressed until disappeared. Finally, the compression went to the densification stage, where the scaffold was densified (picture 7). The failure of this scaffold probably because of the speed was very fast and the layer thickness was very large, resulting in partial weakness of the scaffold.

3.3 FDM of PEEK scaffolds with gradient pores

3.3.1 Surface macro morphology of PEEK scaffolds

With the determined processing parameters, PEEK scaffolds with gradient pores were manufactured using FDM. The diameter of the pores was gradually increasing from outer side to the center of the scaffold (blue arrow) as follows: $0.4\text{--}0.8\text{ mm}$, $0.6\text{--}1.1\text{ mm}$, $0.7\text{--}1.2\text{ mm}$, and $1.0\text{--}2.6\text{ mm}$, as shown in Figure 6. Han et al. [38] proved that a scaffold with pores in size of $483\text{--}905\text{ }\mu\text{m}$ provided more space for tissue ingrowth. In this study, the pore size was larger than $400\text{ }\mu\text{m}$, which was able to provide more room for the tissue and cells ingrowth, migration, and proliferation. Some melts were extruded across the pores (red arrow), leading to some partial shelter (Figure 6a, b, and d) and a whole block (Figure 6c). Fortunately, there were some micro pores ($10\text{--}60\text{ }\mu\text{m}$) on the shelters (red rectangle, Figure 6e–h), providing ways for tissues to penetrate. In addition, micro-pores were showed on the surface of scaffolds (red rectangle) and the wall of pores. As analyzed previously, fibrous tissue was able to penetrate into micro-pores in size of $10\text{--}75\text{ }\mu\text{m}$ [36,37]. The dimension of pores in Figure 6a was controlled well, resulting in similar average diameter to that of the designed pores. On the contrary, the pore in the center of the scaffold was larger than the design, probably because the pore was designed very large.

All the pores were interconnected with each other, bonded by scaffold beams, and uniformly transitioned from outer side to the center of scaffolds. This kind of pore transition was in accordance with that of human bones from cortical bone to trabecular bone, indicating that the osteoblasts and mesenchymal cells can attach, migrate, and proliferate quickly. The larger interconnected pores were benefit to the bone ingrowth and osseointegration of implants after surgery [39]. The surface of pores was

Figure 5: Example of a failed compression of PEEK scaffolds.

Figure 6: The surface morphology of PEEK scaffolds with pores gradual between: (a) 0.4–0.8 mm, (b) 0.6–1.0 mm, (c) 0.8–1.2 mm and (d) 1.2–2.0 mm; (e–h) are the enlargers of the blue rectangles in (a–d), respectively.

rough (Figure 6e–h) due to the swell of PEEK melts. Rough surface was significantly important for the osseointegration of implants [40], and could enhance the attachment, migration, and differentiation of cells for bone forming [41].

3.3.2 Mechanical properties of the PEEK scaffolds

Figure 7 shows the tensile curves of the scaffolds and the effect of porosity on the tensile strength and modulus of

scaffolds. It can be seen from Figure 7b, with the increase in the pore size, the porosity of the scaffolds increased from 31.89 to 58.7%, but the strength and modulus decreased from 34.74 and 4694.32 MPa to 18.47 and 2496.49 MPa, respectively. The low strength and modulus of sample P4 were probably because of its larger gradient pores. During the tensile procedure, the samples showed obvious yield plateau (Figure 7a). Although the tensile strength and modulus decreased with the increase in the porosity, the yield plateau became longer. The longer plateau of scaffolds P3 and P4 was probably because

Figure 7: The relationship between: (a) strength and strain and (b) porosity and strength, modulus (P1, P2, P3, and P4 represent the scaffolds with pores gradual between 0.4 and 0.8 mm, 0.6 and 1.0 mm, 0.8 and 1.2 mm, and 1.2 and 2.0 mm, respectively).

Figure 8: The relationship between: (a) strength and strain and (b) porosity and strength, modulus (P1, P2, P3, and P4 represent the scaffolds with pores gradual between 0.4 and 0.8 mm, 0.6 and 1.0 mm, 0.8 and 1.2 mm, and 1.2 and 2.0 mm, respectively).

of the overlapping interlayer around the central pore (Figure 6c and d). The result indicated that the anti-deforming capacity of scaffolds with larger pores and porosity was enhanced.

Figure 8 shows the compression curves of the scaffolds and the effect of porosity on the compressive strength of scaffolds. With the increase in pore size from 0.4–0.8 mm to 1.2–2.0 mm, the porosity increased from 31.89 to 58.7%, but the maximum strength decreased from 370.42 to 197.83 MPa (Figure 8b). The yield strength rose up moderately first and reached the peak at scaffold P3 (40.06 MPa), followed by a dramatic drop to the bottom (26.24 MPa). It should be noticed that although P4 had the lowest strength, its yield plateau was the longest, showing the highest anti-deforming capacity among the four kinds of scaffolds (Figure 8a).

The tensile strength and compressive strength of human's cordial bone were provided as 50–150 MPa and 106–215 MPa by Wang *et al.* [42] and Lawson and Czernuszka [43]. Morgan and Keaveny [44] concluded the mechanical properties of trabecular bone: the tensile strengths for the vertebra, proximal tibia, and greater trochanter were 1.72, 4.5, and 2.44 MPa, respectively; the compressive yield strengths for vertebra, proximal tibia, and greater trochanter were 2.02, 5.83, and 3.21 MPa, respectively. In this study, the compressive yield strength was between 26 and 36 MPa, and the tensile strength was in the range of 18–35 MPa. Both the compressive and tensile strengths of scaffolds were between the trabecular bones and the cordial bones. Meanwhile, the scaffolds were designed to integrate the cordial and trabecular bones into one piece. Therefore,

Figure 9: The tensile fractural morphology of PEEK scaffolds with pores gradual between: (a) 0.4 and 0.8 mm, (b) 0.6 and 1.0 mm, (c) 0.8 and 1.2 mm, and (d) 1.2 and 2.0 mm; (a1) and (a2), (b1) and (b2), (c1) and (c2), and (d1) and (d2) are the enlargers of the blue rectangles in (a–d), respectively.

the scaffolds manufactured using FDM can satisfy the loading requirements of human bones.

3.3.3 Tensile fractural morphology of PEEK scaffolds

Figure 9 shows the tensile fractural morphology of the PEEK scaffolds manufactured using FDM. All the scaffolds fractured through the cross of pores were the weakest part of the scaffold. Four kinds of fractural surfaces were unsmooth, showing various degrees of overlapping structure between layers, which indicated that the interlayer bonding was strong. The overlapping (green rectangle) was at the two sides of the center pore in Figure 9a and b, and was around the center pore in Figure 9c and d. This phenomenon showed that the scaffolds with higher porosity and larger pores possessed stronger interlayer force that needed more energy to break the part. There were some gaps between layers (blue line) in fracture surfaces of Figure 9a2, b1, and c2, which showed that the combination between layers was not well during the FDM processing. The interlayer gaps expanded further and developed to macroscopic fracture under the loading of tensile, leading to the failure of the scaffolds. A craze shown in Figure 9d1 generated in the fractural surface of scaffold with 1.2–2.0 mm of gradient pores. Literature showed that the craze can consume lots of energy for propagation, which in turn restricts the growth of craze itself [25]. Therefore, the craze was benefit to improving the toughness of PEEK scaffolds. Meanwhile, some micropores (red rectangle) were found in Figure 9a1, b1, c1, and d2 along the printing lines (blue line), where air was grasped during the FDM process. Those air pores will prevent the force transfer and resulted in the failure of the scaffold.

4 Conclusion

This paper studied the effect of processing parameters of FDM on the porosity and compressive strength of PEEK scaffold with uniform pores (0.8 mm of diameter). The platform was modified by pasting a PC plate on it. The parameters were determined as follows: the nozzle temperature of 410°C, the printing speed of 20 mm/s, and the layer thickness of 0.1 mm, by comprehensively considering the porosity and the strength of PEEK scaffolds. With the determined parameters, four kinds of PEEK scaffolds with gradient pores (0.4–0.8 mm, 0.6–1.0 mm, 0.8–1.2 mm, and 1.2–2.0 mm) were manufactured using

FDM. Those pores were interconnected and gradually increased from outer side to the center of the scaffolds. The interconnected pores and the rough surface of the pores can allow the attachment, migration, and differentiation of cells for bone forming. The results of experiment revealed that the porosity of scaffolds was in the range of 31–59%, and the tensile strength, compressive max strength, and compressive yield strength are between 18–35 MPa, 197.83–370.42 MPa, and 26–36 MPa, respectively. The mechanical properties of the scaffolds can satisfy the loading requirements of human bones. Therefore, the PEEK scaffolds have a potential to be used in tissue engineering as implants.

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