On the Design, Coating and Drying Processes of Pellet-Based Extrusion for Additive Manufacturing of PEEK Material

C.-Y. A. Liu, J.-W. Tseng, C.-W. Pan, A.-B. Wang*
National Taiwan University, Institute of Applied Mechanics
*E-mail: abwang@spring.iam.ntu.edu.tw

Abstract

Additive manufacturing (AM), also known as 3D printing, has been considered as the next big trend that would potentially spread as that of mobile phone in last decades. However, there is still no commercial 3D printer for polyetheretherketone (PEEK) material, which is well-known for having excellent biocompatibility and desirable chemical resistance properties in high temperature, due to its high melting point, high viscosity (300,000 cP) and special adhesion & cleaning problems in the operation process. In this study, skipping the commonly used filament feeding in AM for the first time, we've successfully developed a low-cost extrusion-based AM for PEEK material directly from raw pellets to 3D structures with features of easy operation and maintenance. Exchangeable extrusion head modules for plane- and line-typed fabrication have been realized for customized PEEK biomedical applications. The minimum dry film is 50 µm with good surface roughness. The line printing speed is up to 2,000 mm^3/min from the common limit (e.g., ~150 mm^3/min for nozzle in 0.4 mm diameter) of filament feeding. By suitable selection of the operation parameters within the coating window and substrate conditions, different artificial intervertebral cages and structures with designed porosity have been successfully manufactured. The related assessment on mechanical properties was also investigated to meet the strength demands of cortical bone. It is highly expected that the patients can be benefited through the customized filling(s) with a much shorter recovery time after the operation by the quick spreading of the new generalized AM for special biocompatible materials.

Introduction

Additive manufacturing (AM) comprises a suite of material science, opto-electrics, mechanics, and computer aided design (CAD) critical to rapid fabrication spanning from tissue engineering (e.g., cell scaffold for reconstruction and organ implants) to various kinds of prototyping needs[1-3]. In the present market, 3D printing could be reached by stereo-lithography apparatus (SLA), fused deposition modelling (FDM), laminated object manufacturing (LOM), and selective laser sintering (SLS)[4-7], Among these production techniques, FDM is viewed as the most economical way for fast idea construction due to its relatively low threshold in technical barriers and can be easily developed in general computer aided design (CAD) laboratories. However, there are still several complaints with FDM, including of local weak strength perpendicular to building axis, residual shear force caused delamination, and time consuming [4, 5]. These plights are even more crucial when the user is dealing with high viscosity material (e.g., polyetheretherketone). Previous studies have shown that PEEK demonstrates a high degree of biocompatibility and thus is permissible as a material for medical implants. PEEK possesses a mechanical strength comparable to that of bone and thus seems quite suitable for use as an intervertebral implant. Additionally, PEEK distinguishes itself through high durability, high chemical, thermal resiliency, favorable friction and wear properties as well as the characteristic of radio-transparency, which enables radiological examination of the cage position. However, market available PEEK intervertebral cages are often made by injection molding with typical drawbacks of lacking customization flexibility. A low-cost AM for PEEK material directly from raw pellets to 3D structures without any need of special operation and maintenance processes is thus developed in this study. Moreover, to save the operation time and enhance the printing quality, a plane-typed extrusion head module has been added to the traditionally line-typed 3D printing system. In addition, different 3D structures have been fabricated to test its performance and system characters.

Methodology

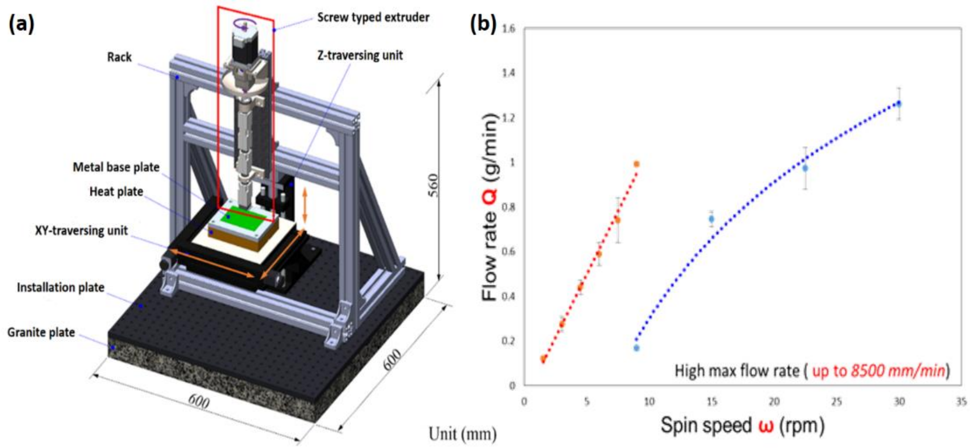

Fig. 1: System of screw-typed AM for PEEK material and the flow rate calibration in line extrusion. (a) The schematic system diagram; (b) flow rate calibration for different extrusion spin speed of 0.4 mm (red) and 0.3 mm (blue) nozzle.

A schematic diagram of this screw-typed AM for PEEK material is shown in Fig.1a. The screw was designed as three phases to achieve the function of feeding, compression, and metering. The temperatures of each phase and substrate were all controlled to ensure an acceptable coating window. In this study, a heated base plate with an IR heater was used to control the surface tension of each newly extruded layer for preventing delamination. The relationship between flow rate and spin speed was also calibrated as shown in Fig.1b. The red line and blue curve indicates the flow rate of 0.4 mm and 0.3 mm in nozzle diameter, respectively. The software was written by LabVIEW, acting as a parser to transform G-code commands from commercial slicing program (Reptier-host) into 3 axes of moving segments with specific pulse width.

Results and Discussions

In the plane extrusion, we firstly measured the coating window of PEEK material with controlled metal base plate temperature (see Fig.2a). The minimum dry film reached by the upper limit of coating window was 50 μm in this study. The multi-layered surfaces and the AFM surface roughness measurement are shown in Fig.2b-c. The extruded film with nanometer level surface roughness and the resolution of 50 µm are better than the current LOM process of 150 µm in plastic sheet. In addition to the plane-typed AM, the line-typed AM with high aspect ratio such as: Taipei 101 model, intervertebral cage, corrosion protective sleeve, bio-scaffold and microfluidic chip were also made by two different types of PEEK material (PEEK 90G and PEEK 450G) to demonstrate our capability of PEEK FDM with a better resolution of up to 150 µm compared to that of 400 µm in commercial FDM machine (see Fig.3). This low-cost extrusion based AM system has not only showed its integration potential but indeed also opened the gate for customizing PEEK material in medial application feasible.

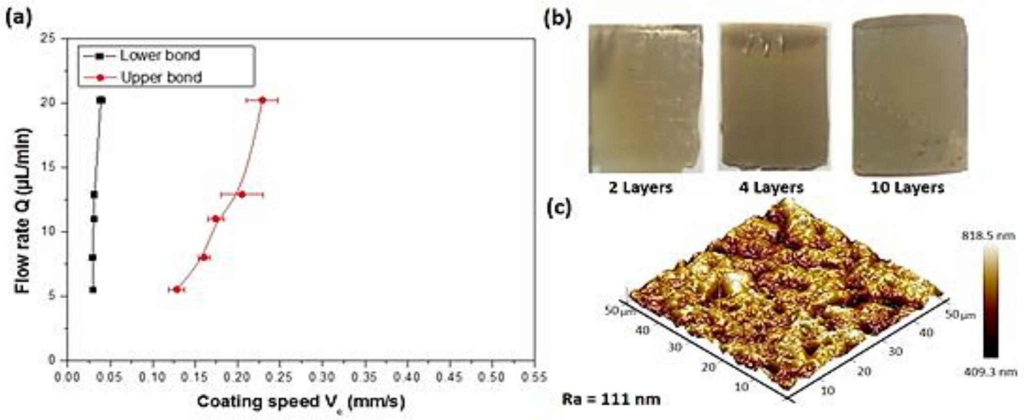

Fig. 2: Plane-typed AM for PEEK. (a) The coating window of PEEK ; (b) multi-layered surfaces; (c) surface roughness analysis for minimum dry film by AFM.

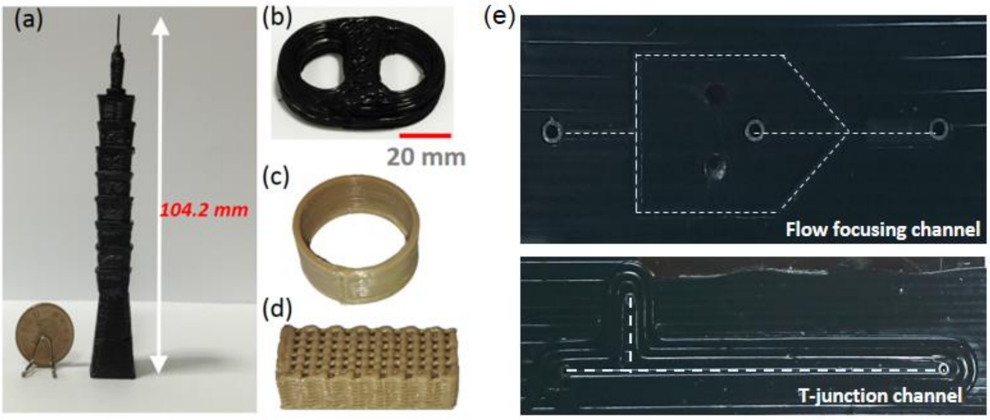

Fig. 3: 3DP PEEK structures. (a) Taipei 101 model; (b) intervertebral cage; (c) corrosion protective sleeve; (d) bio-scaffold; (e) microfluidic chip. The black and yellow colored structures were made by PEEK 90G and PEEK 450G, respectively.

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