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A system for selectively encapsulating porogens inside the layers during additive manufacturing: From conceptual design to the first prototype

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ABSTRACT

Additive manufacturing (AM) has greatly expanded the range of part fabrication to encompass both geometrical complexity and material variation. However, challenges still remain with respect to the implementation of AM technologies. One such issue is related to the de-powdering step required for the removal of support powder inside internal channels and voids during powder-bed AM approaches. This study proposes a novel design and methodology for selectively encapsulating the sacrificial paraffin particles inside the powder layers during the binder jet AM process. The paraffin particles will be generated by punching through the sheet of material which includes a mesh structure carrying a thin layer of wax. Several experiments were designed to evaluate the performance of the proposed system, particularly the effect of input parameters on the size, shape and number of porogen particles as well as their distribution on the substrate. The obtained results revealed the direct influence of mesh structural properties on the porogen particle morphology. Moreover, applying the lower voltage (8 V) and needle diameter (0.28 μm) to separate the porogen improved the repeatability of the range of data ($52 \pm 3\%$–$80 \pm 12\%$), distributing the particles in the area less than 1 mm distance from the center of needle. Then, four categories of the samples were designed for the AM process, 3 samples including porogen of different sizes, and one control sample. The porosity of the specimens measured after sintering process did not show any significant variations among the samples ($35.5 \pm 1\%$–$37.7 \pm 5\%$), due to the limited number of encapsulated porogen. The average diameter of the pores, after removing porogen during the heat treatment phase, illustrates the close similarity to the porogen particles size.

1. Introduction

Functionally graded structures (FGS) with different levels of porosity or variation in materials within the structure have a wide range of applications. According to studies of manufacturing of bio-substitutes such as bone implants and bone scaffolds, pore size and distribution as well as pore interconnectivity are some of the factors shown to have a significant impact on bone tissue in-growth [1–3]. In addition, level of porosity affects the mechanical properties of the substitute, such as mechanical strength and stiffness, which can be tailored to mimic the tissue properties. All of these properties determine the stability of an implant in a patient's body [4]. Heterogeneous structures would include open or closed cells, depending on the application for which they are designed [5].

Methods for manufacturing FGS can be divided into two groups: conventional and additive manufacturing (AM) techniques. Difficulty in control of the cell size and their distribution is one drawback of conventional methods. On the other hand, AM approaches offer a more promising solution to overcome this problem [6]. AM fabrication techniques create three dimensional (3D) objects from a computer-aided-design (CAD) model in a layer-by-layer fashion [6,7]. Several methods are addressed in the literature under the AM categories [8].

In powder bed AM methods such as binder jetting [9], one of the challenges is de-powdering [10], specifically from small internal features or encapsulated cavities inside samples. De-powdering refers to the removing excessive powder particles, including the particles surrounding the sample and those trapped inside the internal cavities. A number of methods have been used for de-

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powdering, such as applying force throughout vibration [2], air pressure [11]· and boiling fluid inside the internal channels [12]. However, due to the delicacy of the green samples in binder jet AM, there is a limitation on the amount of force to protect the structural integrity and resolution of the internal features [12,13].

One solution for this problem is to encapsulate sacrificial porogen particles at selected points of each layer. This step will be followed by removing the porogens throughout different methods such as leaching, dissolving, heat treatment, etc. [14–19]. In some applications, porogen material can be left as part of the final structure to provide an specific property [20].

The aim of this study is to present a new methodology for embedding porogen particles inside the binder jet AM-made samples while the particles are in solid phase in each stage. Manufacturing heterogeneous structures by dispensing a UV sensitive polymer on each layer and by solidifying the material via exposing a UV light source has been under investigation by our group [21,22].

Different methods of solid micro-particles handling have been studied including the contact [23,24–26], and non-contact based approaches [27–32,37]. The main motivations of this article for a new methodology are as follows: complexity of the design, control and repeatability of the experimental data caused by the effect of interfacial forces, limited range of the particle size and number, possible powder bed rearrangement throughout the suggested particle releasing method, as well as the overall expenses and spatial limitation on the custom design binder jet AM system [21].

In this work, we propose a novel design based on an idea of separating the porogen particles from a thin sheet of material by a simple punching action. Pure paraffin/wax is selected as the sacrificial porogen in this study. The specific properties of paraffin, such as formability, low melting temperature, low electrical conductivity and high volume expansion during melting, have made it a suitable candidate for a wide range of applications, including indirect AM [33], energy storage [34,35], porogen particles [36,37], etc.

To investigate the feasibility of the proposed concept, first a prototype of the system, so-called Porogen Insertion Mechanism (PIM), was developed and several experiments were designed to study the effect of system inputs on the number, size, shape and distribution of the porogen particles. After evaluating the results of the characterization step, four categories of the samples were designed and additive manufactured from titanium (Ti) powder through a combination of the binder jet AM method and PIM. The three groups included one layer in which the paraffin porogens were embedded. The last sample group was studied as a control sample. To ensure the complete degradation of the selected paraffin products after sintering and design a heat treatment protocol, Thermogravimetric analysis (TGA) was performed on the wax materials. After the sintering process, the porosity of Ti samples, by applying the Archimedes method, was measured. The dimensional deviation of the cavities, as a result of porogen removal, was determined through analyzing the SEM data.

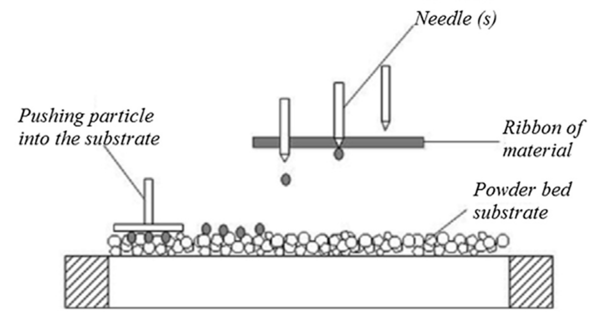

Fig. 1. Schematic image of inserting porogen at selected points.

2. Methods and materials

2.1. Design and characterization of the system

The schematic of this method is presented in Fig. 1. In this approach, first the porogens are separated from the sheet (ribbon) of sacrificial material by activating a needle. Then, they are pushed inside the powder bed to prevent the migration of porogens from the designated location when the new layer of powder is spreading in the next step of 3D printing.

The porogen insertion mechanism (PIM) system includes three main components: punching and pushing head, thin sheet (ribbon) of sacrificial material (Fig. 2a), and a control board. The punching head includes a linear motion module, which moves the needle(s) over the sheet of sacrificial material, a needle-actuator (solenoid) assembly, and a bracket to push the particles inside the powder bed. The PIM is attached to one of the Z-axises (Fig. 2b) of our custom made binder jet AM system [21], to adjust the working distance with each substrate. Design of the system was completed in SolidWorks [SolidWorks Corp., Concord, MA]. To control the system, an electronics board, including an Arduino board [Arduino Uno, Italy], a motor controller [Easy Driver v4.4, Schmalzhaus], and freewheeling diodes, was designed and assembled. Given the space limitations for mounting the system and available resources for the first prototype, the PIM mechanism was developed to fulfill the minimum requirements for system operation.

To build the sheet of sacrificial material, paraffin/wax [Tealights, China] was heated up to 100 °C to liquefy. Then a piece of a mesh was placed inside the melted wax and pressed to result in a layer thickness of 150–300 μm. Afterward, the wax-mesh combination was immediately placed into the water at room temperature to

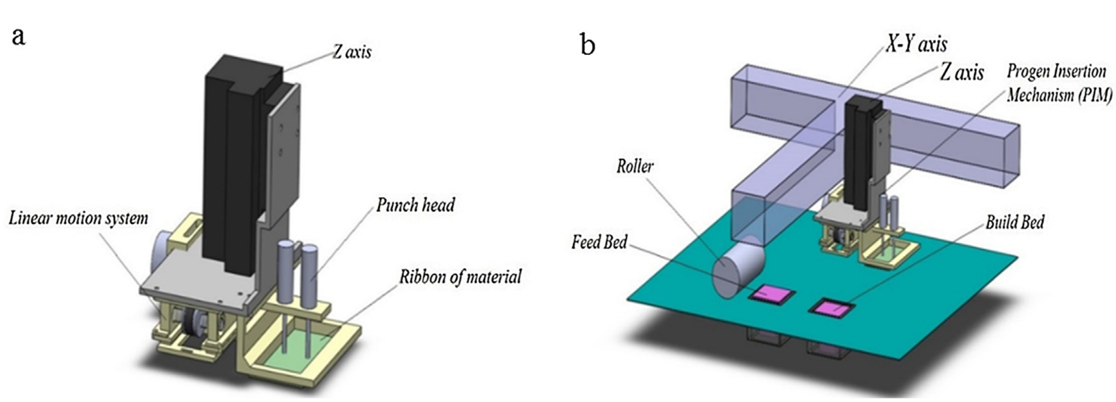

Fig. 2. The main mechanical components of PIM (a), and assembly of it on the multi-scale porous 3D printer's gantry robot [21].