DRY POWDER MICROFEEDING SYSTEM FOR SOLID FREEFORM FABRICATION

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Abstract

Second generation SFF techniques allow both composition and shape to be downloaded directly from a computer file so that 3D functionally graded materials (FGM) can be assembled. Methods for multi-material deposition are also needed in combinatorial research, colour management and pharmaceutical dosing. In this work, computer-controlled microfeeding systems using ultrasonic vibration of a capillary were built. A wide range of stable flow rate control and switching control were achieved in the acoustic vibration system, and uniform powder doses were obtained in the ultrasonic system. The experimental results show that the nozzle diameter, transmission fluid depth, waveforms, voltage amplitude, frequency and oscillation duration all influence the dose mass. Among these factors, the nozzle diameter, voltage amplitude and oscillation duration can be used to control the dose mass. Raster printing of patterns with various resolution and dot size are demonstrated.

Introduction

In selective laser sintering (SLS) or three dimensional printing (3DP), layers of powder are laid down, usually with a roller, and the forming areas are either scanned by a high power laser or printed with binders while the non-forming areas remain as loose powder to support subsequent layers [1, 2]. This means the whole object must be made of one material, although in 3DP small amount of doping inks could be printed on the powder bed by changing the ink composition [3] and functional gradient materials (FGM) can be made by depositing a different powder composition in each layer[4]. There is now an interest in incorporating many materials into one component through so-called functional gradients, in which programmed concentration profiles are built in to avoid steep concentration interfaces by concurrent deposition and blending of several different powders. This is becoming possible with direct ink-jet printing [5] and selective laser sintering [6, 7].

At the same time, the pharmaceutical industries also need effective techniques for microfeeding of fine powders. Dispensing, dosing and blending of several powders by computer control, allow large potential formulation design spaces. During the early stages of the development of new drugs, the availability of candidates is often limited to a few grams of the newly synthesized powders. For example, the solubility of compounds is one of the screening criteria, and requires automated tools to perform comprehensive early-stage solubility studies.

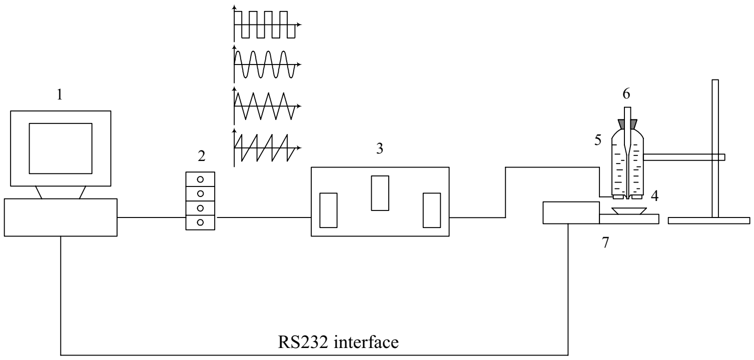
New methods for dry powder microfeeding are emerging in response. There are several distinct methods for powder metering and dispensing [8]: pneumatic methods, volumetric dosing, gravimetric dosing, screw and auger dispensers, electrostatic control to meter powders, magnetically mediated flow enhancement for controlled powder discharge of cohesive powders, acoustic or ultrasonic controlled powder dispensers and powder feeding devices based on excitation of a progressive wave in a lossy ultrasonic transmission line. Microfeeding by ultrasonic vibration is one of the promising methods for fine powders.

There are a few attempts in the past few years using ultrasonic vibration to dispense dry powder for multi materials solid freeform fabrication. Matsusaka et al. [9] first studied the microfeeding of fine powders in a capillary tube vibrated by 20 kHz ultrasound generated by a piezoelectric transducer. Takano and Tomikawa [10] built feeding devices based on excitation of a progressive wave in a lossy ultrasonic transmission line. Li et al. [11] studied the mechanism of ultrasonic dispensing. These studies only focus on continuous dispensing with controllable flow rate. Yang and Evans [12,13] studied the factors and mechanism affect the initiation and closure of the flow in vibration controlled dispensing system, which are very important in short dispensing periods. An intermittent dispensing device [14], a dry powder printer, was studied to increase the accuracy of micro-dispensing. Short pulses of ultrasonic vibration were used to dispense the dry powders in "drop" format, analogous to the drop-on-demand ink jet printer. The dispensing mechanism [15], drop uniformity [16], and different design of dispensing nozzles [17] were studied. In this paper, we investigate the possibility of pattern printing and drop size control.

Experiment details

The micro dispensing device comprises a computer, an analogue waveform generator (Model: PCI 6733 DAQmx Card, National Instruments Corporation), an electrical controller (Power amplifier: PB58A, Apex Co., Tucson, Arizona, U.S.A), a piezoelectric ring (Model: SPZT-4 A3544C-W, Size: 35mm×15mm×5mm, Resonance frequency: 44 kHz, MPI Co., Le Locle, Switzerland), a glass nozzle (capillary tube), a water tank, and a microbalance (2100 mg ± 0.1 μg, Sartorius AG, Goettingen, Germany), as shown in Figure 1. The dispenser was positioned over a three-axis high performance linear motor table (MX80L Miniature Stage, Parker Hannifin Automation, Dorset, UK) capable of high acceleration (39.2 ms^{-2}) and speed (100mms^{-1}). The table was driven by Labview software (National Instruments, US).

The computer and NI 6733 D/A card generate a voltage signal, which can be varied with different waveforms, frequencies and amplitudes. The waveform outputs to the controller, which includes three parts: direct current power supply, power amplification circuit and tuning circuit. The signal voltage was subjected to a gain of 10 when applied to the transducer. The piezoelectric transducer excited by the high frequency signal (>20 kHz) transmits the vibration to the capillary through water. The powder dose mass can be weighed by the microbalance, which transmits the data to the computer via the RS232 serial-port. The inner diameter of the water tank is 40 mm. The feed tubes consisted of glass capillaries drawn down from 10 mm (i.d.) tubes. The upper section acts as the hopper and is used to store the feed powder. A piezoelectric ceramic ring was attached to the bottom of the tank by an adhesive frequently used in ultrasonic cleaning tank construction (9340 GRAY Hysol Epoxi-Patch Structural Adhesive, Dexter Co., Seabrook, USA).



1. Computer; 2. D/A card; 3. Electrical controller; 4. Piezoelectric ring;
5. Water tank; 6. Nozzle; 7. Micro balance or 3D table

Figure 1. Experimental arrangement of the microfeeding system.

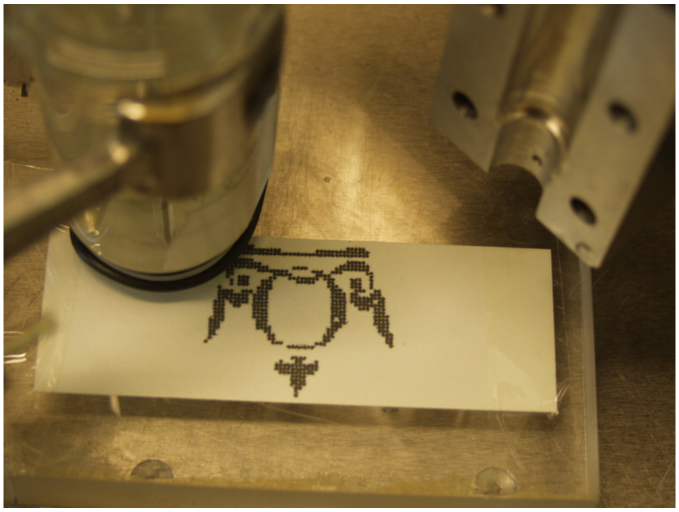
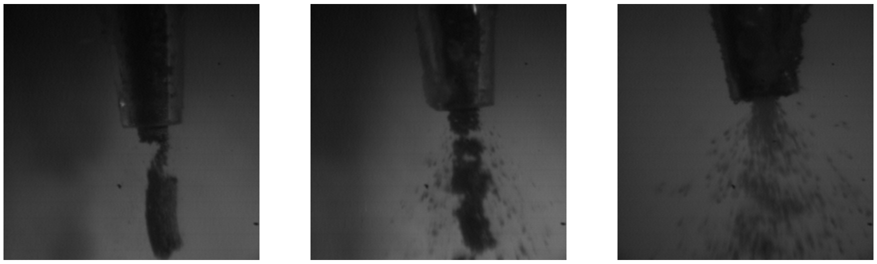


Figure 2. Pattern printing with nozzle mounted on XY table.

Results and Discussion

1. Effect of powder dispensing parameters on microfeeding

The effects of process parameters for different powders have been identified [15]. Dispensing by ultrasonic vibration depends on the powder structures that develop in the capillary tube which can be divided into three types: arching, plugging and blocking. Powders which are cohesive and of low density tend to block the capillary tube as they descend from the hopper, generating many plugs in the capillary. The relatively less cohesive and denser powders cause the arching phenomenon which allows controlled dispensing. Depending on cohesion, the powder falls as partially compacted columnar rods, clots or cluster or discrete particles, as shown in **Figure 3**.



(a) (b) (c)

Figure 3. Different drop forms (a) reinforced columnar rod (H13 tool steel) (b) clots or clusters (WC) (c) dispersed discrete particles (glass beads).

The nozzle diameter, water depth, waveform, voltage amplitude, frequency and oscillation duration all influenced the mean dose mass. Some of these variables need to be fixed and they cannot be used to control dose mass. Feeding should be carried out at the minimum impedance resonance frequency. The water depth affects the resonance frequency of the coupled system and at a given frequency, there is an ideal water depth for inducing the maximum feed. Waveform influences acceleration modes of the piezoelectric element and modifies dispensing; the square wave excitation is preferred for microfeeding. A range of different nozzle diameters is needed to accommodate fine powders with different densities and particle diameters for microfeeding, there being upper and lower diameter limits for each powder. The minimum dose mass is, in turn, different for different diameter nozzles. Dose mass increases monotonically with excitation amplitude. As the oscillation duration is prolonged, the dose mass increases and for some powders, this relation is almost linear.

The experimental results show that microfeeding is best controlled by the voltage amplitude and oscillation duration under square wave actuation. A limited range of nozzles diameters is suited to a given powder. The range of frequency is very narrow for resonance and hence maximum dosing. The frequency and water depth are thus fixed for a given dispenser configuration and cannot be used to control the dose mass.

2. Drop size on substrate

After dispensing, the dry powder dose falls on the substrate and spreads. If the nozzle is close enough to the substrate, the spreading of the dose due to the collision is a minimum. Suppose that the powder piles in a conical shape with radius ***r*** and height ***h***. the volume of the cone is

$$V = \frac{1}{3} h \cdot \pi r^2 = \frac{1}{3} \pi r^3 \tan\alpha \qquad (1)$$

where α is angle of repose. Then the radius of the dose on substrate is

$$r = \sqrt[3]{\frac{3m}{\rho\pi\tan\alpha}} \qquad (2)$$

where ***m*** is the mass of the dose, $\boldsymbol{\rho}$ is apparent density.

For WC powder, the angle of repose is 36°, and apparent density is 8500kgm^{-3}, the 50µg dose gives ***r*** =0.2mm. The size gives a maximum resolution of 64DPI (Dots per Inch). The result shows a good fit with the experiment (Figure 4-6). In Figure 4-6, a logo of Queen Mary University of London is printed with 50µg doses at different dot pitch and substrate to demonstrate the pattern printing capability. The logo has pixels of 50x50.

In **Figure 4**, the logo was printed with 42 DPI (0.6mm pitch) on plain paper. The dots are clearly discrete, with about 0.1-0.2mm gaps between adjacent dots.

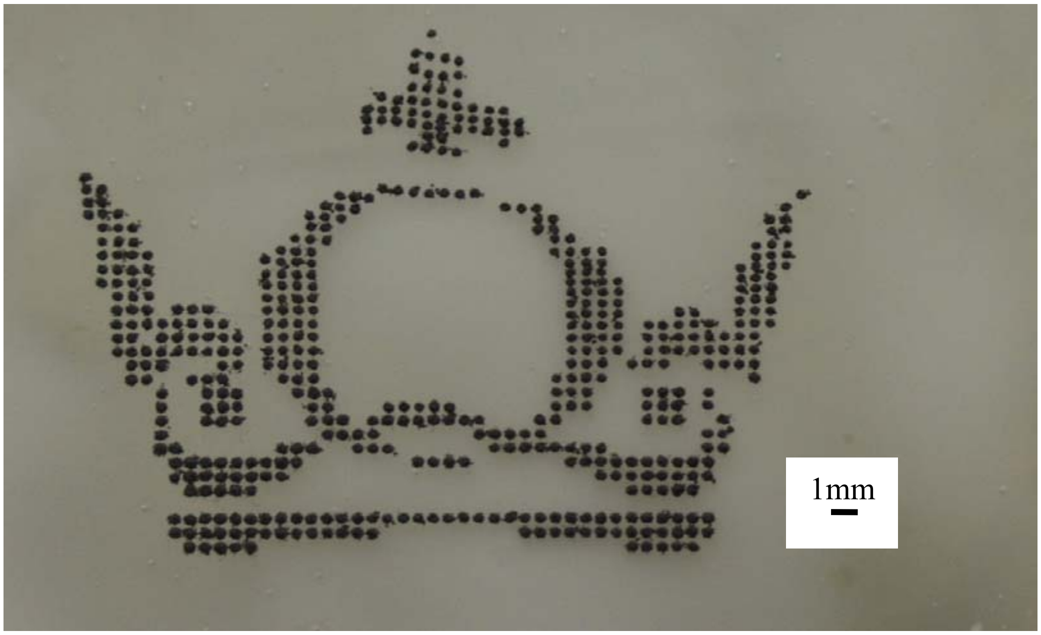


Figure 4 Pattern printed with 42DPI (0.6mm pitch) on paper.

In Figure 5, the logo was printed with 56 DPI (0.45mm pitch) on alumina slides pre-coated with a thin layer of liquid resin mixed with initiator. The resin has a working time of about 1 hour before polymerization and was used to keep the dots on site after printing. Due to the low viscosity and non-uniform thickness of the resin, a few particles drifted from the sites. The resin also causes a slightly bigger dot size due to the drifting of the powders.

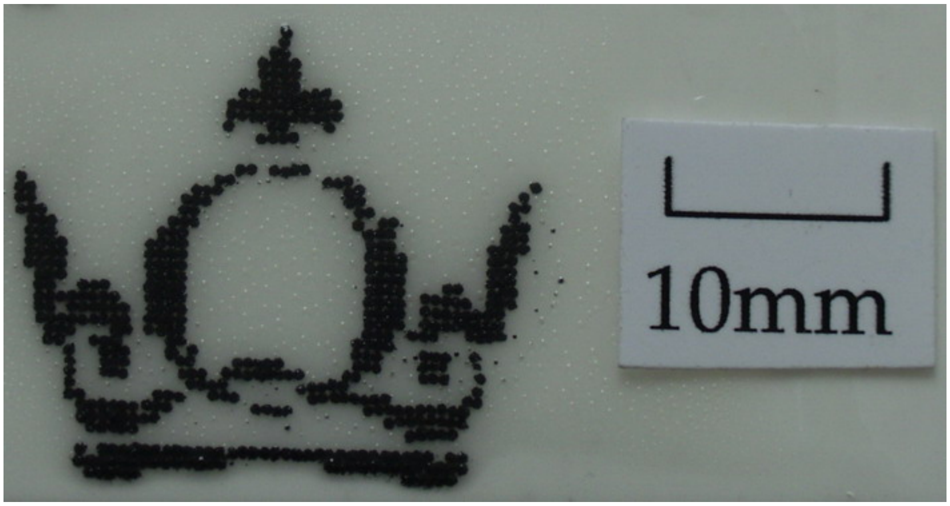


Figure 5 Pattern printed with 56DPI (0.45mm pitch) on alumina slide pre-coated with resin.

In Figure 6, the logo were printed with 64 DPI (0.4mm pitch) glass slide pre-coated with a thin layer of liquid resin mixed with initiator. The adjacent dots were contact and overlapped with each other giving a dense filling.

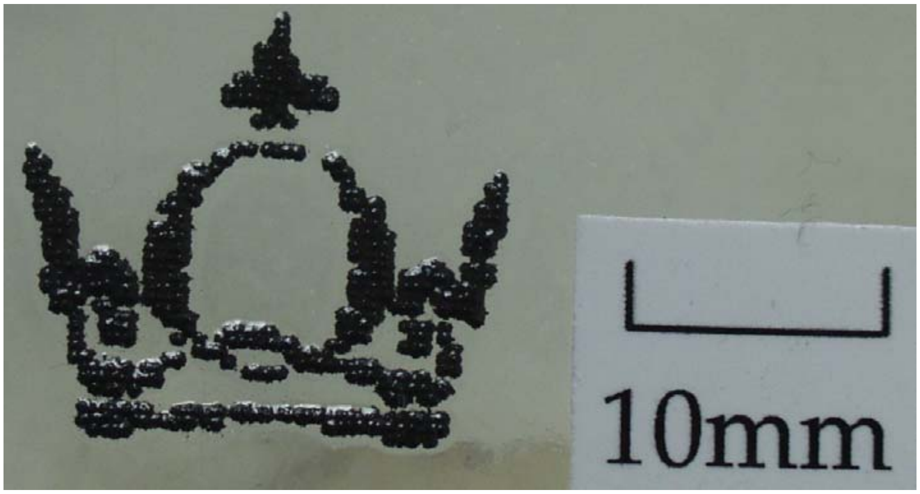


Figure 6 Powder pattern printed with 64DPI (0.4mm pitch) on glass slides pre-coated with a thin layer of resin.

In **Figure 7**, a 5x5 matrix of dots were printed with increasing dose mass from left to right and from top to bottom. The matrix was printed with minimum dose mass of about 50μg and maximum 1mg, by varying the signal voltage from 1V to 5.8V with increasing step of 0.2V.

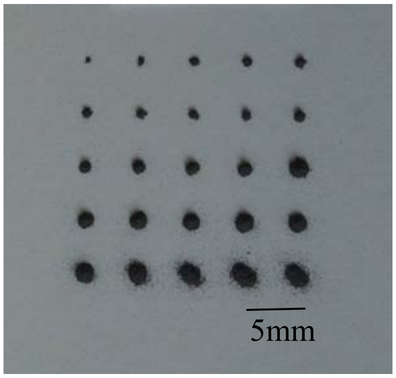


Figure 7. Drop size control (from left to right, from the top to bottom, the mass of the dose were varied from about 50μg to 1mg, with 25 steps) (f=44.8kHz, t=0.05s).

Conclusions

A computer-controlled microfeeding system using ultrasonic vibration of a capillary was built. The effect of process parameters for different powders has been identified. A wide range of stable flow rate control and switching control regime were achieved and uniform powder doses were obtained in the ultrasonic system. Drop size on substrate was estimated through the angle of repose and the apparent density of the powder, and the results concur with the experiments. Raster printing of patterns with various resolutions from 42-64 DPI were demonstrated. Dot size can be well controlled through voltage variation.

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