DESIGN OF A MICRO-HOPPER ARRAY FOR MULTI-MATERIAL POWDER DEPOSITION

Suman Das and James Santosa
Department of Mechanical Engineering
The University of Michigan
Ann Arbor, MI 48109-2125

Abstract

We present a concept for creating patterned beds of multi-material powder particles using an array of small-scale hoppers. Using this technique, we propose that to place fine particles of multiple fluidized powders discretely in a thin layer as opposed to depositing an entire powder layer of uniform composition using a roller device or doctor blade. Processing and consolidation of multiple, patterned powders can enable fabrication of composite objects with spatially varying structural and multifunctional characteristics. Although theory on the design of small-scale hoppers is lacking, our design for a hopper, its valving, and its particle delivery system are guided by background theory for large hoppers. A hopper array configuration is proposed, and a calculation for deposition time is presented. Delivery of powder was achieved on a prototype hopper. Experimentally measured mass flow rates were used to justify the use of this hopper with SLS and to guide further design improvements.

INTRODUCTION

The variety of applications for multi-material composite structures is both well established and growing rapidly. However, a present obstacle to continued growth lies in the approaches to manufacturing these types of artifacts. The development of new approaches for fabricating multi-material components is in part dependent upon developing SFF techniques capable of depositing and consolidating multiple materials. In particular, the selective laser sintering (SLS) process is well suited to this challenge. A means of incorporating the delivery of multiple powders in SLS may enable the production of complex, multi-functional and intelligent components.

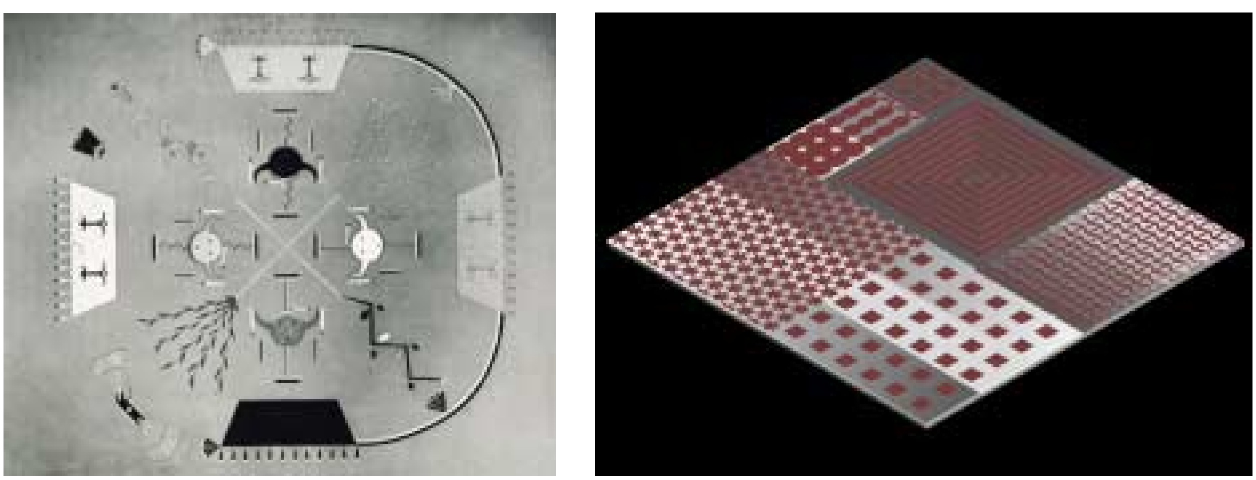

Figure 1. (a) Navajo sand painting, The Arizona State Museum, University of Arizona and (b) Conceptual design of a multiple material, patterned, powder layer for building multifunctional components by SLS.

The concept of 2-D deposition for multiple powders is by no means a new idea. In fact the greatest model for this idea is based on the art form of sand painting as shown in Figure 1a and first described in the context of SFF by Pegna et al [7]. The Navajo and Tibetan monks of earlier centuries have shown that detailed patterning of fine powders can be achieved manually. These artists typically spent several weeks working patiently on a single-layer design. However, the challenge from a layered manufacturing perspective is in successively depositing thin layers of multiple powders quickly and with high placement accuracy. By allowing the consolidation of multi-materials as shown in Figure 1b, SLS has the potential to launch a new manufacturing paradigm that enables fabrication of complex, multifunctional, intelligent components that cannot be fabricated by existing methods. The following sections provide background on the use of hoppers with fine powders, the theory guiding the design of a single hopper and standpipe to an array of these devices, and results of preliminary experiments conducted on a prototype hopper design.

BACKGROUND

In current selective laser sintering machines, powder is leveled over the part-build area by a counter-rotating roller mechanism or a doctor blade. A bed of powder may be quickly rolled over the build area in layers of consistent thickness. Currently the SLS process is limited to fabricating components of only a single composition. However, SLS is capable of simultaneously sintering a variety of powdered materials (metals, ceramics, polymers). This makes depositing and processing two or more different powdered materials side-by-side on the bed feasible. With this in mind, the development of hoppers for delivering dots, sharp lines and prescribed patterns of powder is desirable for use in the SLS process. In fact, those who practiced the art of sand painting used a tool that is essentially a hopper releasing powder to a surface by vibration. A multi-powder deposition device for adaptation to SLS should have more stringent requirements. For the design of our hopper, a number of design specifications were established. According to these specifications, the device should be able to:

1. Deposit arbitrary patterns of multiple powder material (i.e. points, lines, regions) for particles with diameters ranging from 0.1 to 100 µm.
2. Achieve a minimum in-plane feature size of 100 µm.
3. Achieve layer thickness ranging from 25 to 250 µm.
4. Regulate hopper mass flow rate, start and stop flow with minimal time delay.
5. Handle multiple materials with real time composition control.

In an attempt to meet some of these goals, the background research focuses on 3 areas: the relevant properties of powder particles, the design of hoppers, and, flow control and valving techniques.

Relevant Powder Properties

The characteristics of powdered material that must be considered are the size, shape (sphericity), cohesion properties, bulk density, and porosity (voidage). These are most critical to understanding the bulk flow of the solid material, from how it is packed to how it is transported (Shamlou [8], Woodcock and Mason [11]). Cohesive properties can be described as the ability of the bulk material to freely flow based on inter-particle forces (Jenike [3]). One of several methods to measure cohesion property that is of special concern to SLS is the angle of repose (a.k.a. angle of internal friction) of a deposited powder. This is useful for understanding the ability of a poured powder to remain in a stable pile (Stepanoff [10]) i.e. when the deposited lines are settling on the substrate.

For applications over a wide variety of materials, it is important to have a practical method for classifying powders without depending on extensive experiments. The Geldart classification [2] is an appropriate and well-used system for grouping powders by their ability to fluidize. Fluidization is the ability of a uniform bed of particles to expand when an upward stream of gases is distributed from beneath. A bulk material that is well fluidized will have an expanded volume, where particles seem to be floating in the fluid stream, separate from other powder particles. This is advantageous because of reduced inter-particle friction and ability to circulate powders within the bed.

SLS applications require fine powder particle diameter between 0.1 μm to 100 μm, and the bulk material is largely considered non-cohesive (fair to free-flowing in nature). These types of powders would typically fall into the Geldart A classification [2]. An attempt to fluidize such powders relies upon the knowledge of minimum fluidization velocity. This is the velocity of introduced gas at which incipient fluidization occurs in the powder bed or chamber. There are many approaches to gaining values for minimum fluidization velocity, but equation (1) is the rule of thumb for particles in air (Woodcock and Mason [11]).

$$U_{mf} \cong 420\rho_p d_v^2 \quad (1)$$

where U_{mf} = minimum fluidization velocity (m/s)
ρ_B= bulk density of the powder (g/m^3)
d_v = mean particle diameter based on volume (m)
and 420 is an empirical value for particles in air (m^2/g-s).

Hopper Design

A hopper can be described as the lower converging section of any vertical bin for discharging bulk materials. Hoppers can have conical, wedge-shaped, or even asymmetrical designs. Hoppers can also have circular, square, or rectangular orifices. Evidently, the geometry of a hopper design is essential in achieving desired flow properties of the discharged material. The delivery of particles may happen under core flow (first in-last out) or the more desirable mass flow (first in-first out). For the design of a conical hopper, the hopper half-angle, α, and the orifice diameter, D_0 are the most important dimensions to be considered in preventing arching (bridging of particles that blocks flow) and rat-holing (an empty tunnel over the orifice due to core-flow). Jing and Li [5] provide useful information on hoppers for fine powders, stating an effective hopper half-angle of 10.2° or less for maintaining mass flow.

One of the most frequently used theories on flow from hoppers is W. A. Beverloo's modified correlation [1] for mass flow rate in conical hoppers. While there are other similar theories for mass flow rate, e.g. the hourglass theory, these do not take into account the effects of particle diameter. The modified Beverloo correlation is

$$G_s = C\rho_b \sqrt{g + \left(\frac{dp}{dz}\right)_0 \frac{1}{\rho_b}} (D_0 - kd_p)^{5/2} \quad (2)$$

where G_s= mass flow rate of particles (g/s)
C = empirical constant (usually .58) dependent on hopper angle and angle of internal friction
ρ_B= bulk density of the powder (g/m^3)
g = gravitational constant of acceleration ($9.8 m/s^2$)
D_0= hopper orifice diameter (m)
k = empirical constant for particle shape (1.6 for spherical particles)
d_p = mean particle diameter (m).

The term $1/\rho_B\ (dp/dz)_0$ is a modification of the gravitational acceleration term to include the interstitial pressure gradient. Beverloo's correlation states that as particle size decreases, there is an increase in the mass flow rate. Empirical results agree for particle sizes down to 500μm, where actual mass flow rate takes on much lower values than predicted.

An article by Spink and Nedderman [9] presents an experimental and theoretical study on the rate of discharge of fine particles (diameters between 50 μm and 500 μm) under gravity in air from a hopper. These size particles are small enough to be retarded by air resistance when passing through the hopper orifice, but not too small so as to be subject to cohesive effects. In this work, it is believed that the air pressure gradient opposed to the downward flow reduces the flow rate of the particles under 500 μm, and it is also presumed that change in voidage as the hopper converges has a slowing effect as well. The work by Spink and Nedderman used first principles (stress equations for different regions in the hopper) to come up with a theoretical model. They experimentally measured the voidage and interstitial fluid pressure distribution with external probes around the hopper and used these to account for the drop. The result was a downward sloping set of data points for the mass flow rate of particles having less than 500 μm diameter (always higher than actual, but generally following the reducing trend). This is a good basis for the kind of experimentation needed to understand the behavior (voidage changes and pressure distribution) in much smaller hoppers. Our challenge in designing a micro-hopper based powder deposition system for SLS will be to adapt these types of experiments to small scale hoppers.

At the present, most theoretical predictions relate to large, coarse particles on the order of 500 μm diameter that are cohesionless and insensitive to drag. Beverloo's equation is known to be inaccurate for particles under 500 μm diameter. Most hopper theory is valid for large-scale bulk materials handling only. However, the existing theory provides a useful basis on which empirical models, and eventually a working theory for powders under 500μm and orifices around 100μm can be developed.

Flow Control and Valving

There are a number of techniques to starting/stopping flow, from the use of physical barriers such as gate valves, to fitting a hopper with flow aids like vibrating plates. Considering the small particle and hopper sizes we are compelled to modify or combine existing techniques for application to an array of hoppers.

Pegna et al [7] conducted an experiment using a non-mechanical L-valve [6], where powders come to rest in the elbow portion due to their angle of repose. Flow was started by introducing air from an aeration point. The flow rate was proven to be unstable considering the size of the particles. However, this design did not feature a hopper, and the orifice was simply the end of the downcomer. The concept of a hopper valve for Geldart A powders is presented in an article by Jing and Li [4]. In this setup, the flow regime and flow stopping are controlled by maintaining a negative pressure gradient from the hopper orifice to the standpipe. It is our belief that combining the design of a standpipe with L-valve and hopper dimensions according to the Jing and Li criteria can be a strong combination for use with a greater variety of powders.

EXPERIMENTS

Figure 2 shows our prototype hopper design. Some of the features include:

1. A 60mm I.D. glass Buchner funnel and coarse fritted glass disk used as a chamber for fluidizing particles and delivering them to the standpipe.
2. Two angled aeration points at the base of the funnel to fluidize the powder above the fritted glass disk. Fluidized powder travels down the standpipe originating at a hole in the fritted disk.
3. Adjustable tube lengths for the glass standpipe and elbow in 10 mm increments. Glass pieces are joined using photosensitive UV curing resin. The prototype shown has a 150mm long standpipe and 40mm long elbow, both 4mm I.D.
4. An L-valve aeration point angled at 45º to the elbow. The position of the aeration point can also be varied along the standpipe with the use of adjustable tube lengths.
5. Bio Plas, Inc. pipette tips used as micro-hoppers, which feature a half angle < 10.2° and 5mm orifice that can also be trimmed for larger diameters (.75 and 1mm).
6. 100 µm glass beads used for powder for initial testing (bulk density 2480000g/m^3),120 grit sandpaper used as the substrate (depositing surface).

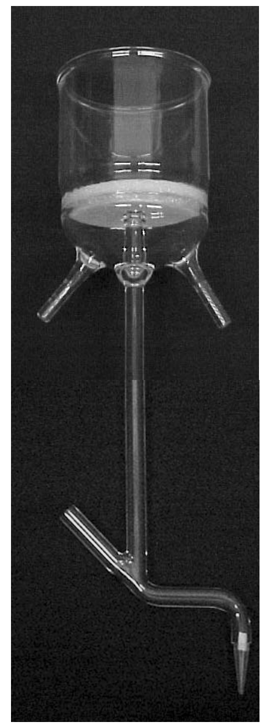

Figure 2. Prototype micro-hopper

RESULTS

Ten trial runs for mass flow rate were conducted on the prototype hopper under both gravity flow and air assisted flow for orifice diameters of 0.5, 0.75, and 1 mm. Our preliminary trials show that the standpipe with L-valve design is fully capable of stopping the flow of powders. The powder will come to rest at the angle of repose (approximately 23°) when the elbow portion of the L-valve remains horizontal. Particles just over the nozzle will continue to flow through until this portion is emptied. Air introduced from the aeration point prefers to fluidize the column of particles in the standpipe rather than push particles over the elbow. Although a higher flow of air will move the powder through the elbow, we avoid interfering with flow settings that may make the powders in the standpipe entrain (bubble out). To restart flow, we preferred to slightly tip the L-valve down – a technique that may possibly be incorporated into later designs.

Nozzle diameter(mm)	Gravity flow or Air assisted	Average mass flow rate (g/s)	Volume delivered per second (m^3/s)	Time to draw a 250 μm high, 6in.(.1524m) line
0.5	G	0.0283	$1.9X10^{-8}$	0.79 seconds
0.5	A	0.045	$3.0X10^{-8}$	0.50 seconds
0.75	G	0.0316	$2.1X10^{-8}$	0.71 seconds
0.75	A	0.0616	$4.1X10^{-8}$	0.37 seconds
1.0	G	0.0717	$4.81X10^{-8}$	0.32 seconds
1.0	A	0.1	$6.7X10^{-8}$	0.22 seconds

Table 1. Results from prototype hopper tests for 100 μm glass beads (bulk density 2480 kg/m^3).

Our mass flow rate results in the third column of Table 1 show that flow rates of a single powder increase with larger orifice diameters. Trials with air entry from the aeration point were conducted at the velocity just below where entrainment in the standpipe was observed. It is believed that the position of the aeration point primarily allows the standpipe's particles to be fluidized, while slightly counteracting the pressure gradient at the nozzle and increasing the flow rate. Flow rate for all diameters were improved by approximately 0.025g/sec with air. Further experiments may reveal whether there is proportional relationship between air-assisted flow and orifice diameter.

Array Theory

Using basic information such as mass flow rate, it is possible to calculate the deposition times of our prototype hopper design its suitability for use with SLS. To compete with the speed of current roller mechanisms for laying powder on a bed, a successful design should be able to deposit a complete layer in a matter of seconds. The following assumptions characterize the ability of our prototype hopper (and eventually a hopper array) to achieve deposition times appropriate for SLS:

Assume that the volume of material deposited per second in m^3/s is:

$$\dot{V} = \frac{G_s}{\rho_B(1-\varepsilon)} \qquad (3)$$

where G_s = mass flow rate of particles (g/s)
ρ_B = bulk density of the powder (g/m^3)
ε = voidage of powder particles, assumed to be 0.4, based on 60% packing density

Also assume that a stationary orifice is capable of depositing a disk of material with the same diameter as the orifice. Therefore, the volume of the disk (m^3) to be filled is:

$$V = \frac{\pi D_0^2}{4} \bullet h \qquad (4)$$

where D_0 = hopper orifice diameter (m)
h = desired height of a disk of material (m)

Therefore the time (s) to deposit a single disk of material with height h is:

$$\frac{V}{\dot{V}} = t = \frac{\pi D_0^2 h \rho_B (1-\varepsilon)}{4G_s} \quad (5)$$

A series of these deposited disks laid side-by-side can be thought of as collectively forming a line. With knowledge of the diameter of the disks, the number of disks that compose a line of desired length is the ratio l/D_0. The overall time,T, required to deposit a line is:

$$T = t\frac{l}{D_0} = \frac{\pi D_0 l h \rho_B (1-\varepsilon)}{4G_s} \quad (6)$$

The last two columns of Table 1 show that the volumetric flow rate and the time required for drawing a 0.010 inches (250 μm) high, 6 inches long line (an estimated minimum length for a powder bed) would be feasible for use with SLS. Even though delivery times for potentially smaller orifice diameters are above 1 second for gravity flow or air-assisted, an array of nozzles that produces a complete layer in a similar amount of time will be faster than current roller or doctor blade techniques. Shown in Figure 3 are two array concepts to be explored for minimizing delivery time to the bed.

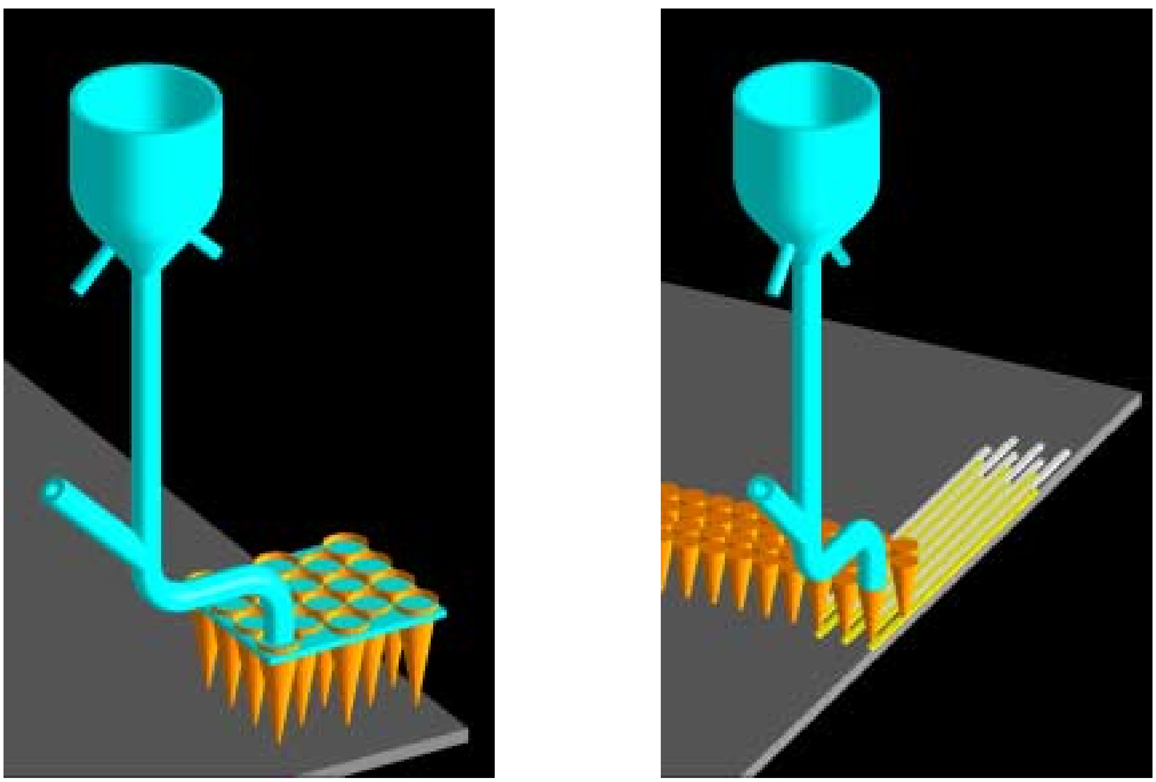

Figure 3. (a) A 4x5 staggered array, and (b) A array covering the entire bed length.

FUTURE WORK

There are many challenges for future work on a micro-hopper array. It is our aim to determine experimentally and eventually theoretically a prediction for mass flow rate in micro-hoppers. Theory should apply to a variety of powders, so a single highly compatible hopper design and model for fluidization with dispensing adjustments can be achieved. Visually, the micro-hoppers are delivering powder with consistent flow rate. However, techniques to aid in understanding all of the phenomena, i.e., determining the pressure at the aeration point and minimum fluidizing velocity in the particle delivery system, need to be determined. Incorporating an XYZ positioning system will yield valuable information on whether our desired minimum feature size for lines and patterns is feasible. Once these goals are achieved, work will focus on the design and control of the array and powder supply system. We look forward to experiments on mixing and depositing powders in gradient fashion with the ability to draw two or more powders from a reservoir supply system

CONCLUSIONS

Existing theory on large hoppers was used to guide the design of prototype micro-hoppers for powder delivery. Information on relevant particle properties and flow control techniques was noted. A prototype micro-hopper design was completed and tested with 100 μm glass beads for both gravity flow and gas assisted flow conditions. Mass flow rates were noted to increase with air-assistance, and measured delivery times were found to be appropriate for use with SLS.

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