A Dry Powder Material Delivery Device for Multiple Material Additive Manufacturing

S. Chianrabutra, B.G. Mellor, S. Yang

Engineering Sciences Unit, Faculty of Engineering and the Environment,
University of Southampton, Southampton SO17 1BJ, United Kingdom

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Abstract

This research is to develop a novel material delivery device for a next generation additive manufacturing system which is capable of directly manufacturing objects by depositing several materials layer by layer. The successful deposition of multiple material layers by using this novel dry powder printing technique reveals its great potential as a means of incorporating multiple materials in the traditional additive manufacturing process since this technology is suitable for a wide range of materials and it has the capability to manufacture 2D layers composed of multiple materials. This paper will outline the basics of the dry powder printing technology and present and discuss selected experimental studies from our research.

Introduction

Currently, most commercial additive manufacturing systems are designed to produce parts from a single material [1]. Multiple Materials Additive Manufacturing (MMAM) using direct inkjet printing technology was pioneered by Evans and co-workers nearly 20 years ago [2] and is now researched by various groups. Objet has commercialized direct inkjet 3D printers and claim that they represent the only MMAM system. However, Objet can only print photopolymer materials, which have limited mechanical properties and other functionalities, compared to direct metal and/or ceramic printing. MMAM is a new technology that can fabricate three-dimensional multiple material (heterogeneous) objects. This technology can create multiple material objects and can vary material compositions within the layer [3]. The ability to print multiple materials from an additive manufacturing system can improve either the mechanical properties of the parts or provide additional functions to the 3D printed parts [4]. MMAM technology has the potential to become an important manufacturing resource for the next generation of AM technology. This is because single material AM systems cannot fulfil the requirements of some applications that require multiple material objects from one machine, such as compliant mechanisms, embedded components, 3D circuits, human tissues, medical compatible implants etc. Moreover, the next generation of AM technology should provide full functionality, offer changeable material systems, and give the entire bonding system at an affordable price [5-7].

Multiple material objects are more interesting and will be highly important in many industrial applications. Many research institutes and companies have been developing AM technologies to allow more materials to be used in single material AM technology, and to improve the properties of the AM part and to enhance the capability of the basic process [4]. Powder based materials are very important as they can provide a wide variety of material options. The Dry Powder Printing (DPP) technique is one of the promising techniques available to dispense fine powders [8]. Among the DPP techniques, the ultrasonic dispensing method has many significant advantages for depositing fine powders uniformly and controllability and has the ability to handle a wide variety of powder materials. In most of the current powder based AM systems, powders are spread using a roller onto a powder bed which made it impossible to fill multiple materials without cross-contamination [9, 10]. Therefore, it is essential to develop processing technologies that can handle fine powder particles for use in material delivery devices for the next generation of AM systems. However, processing and handling powder materials is very challenging due to their unique properties. To deposit such materials it is necessary to understand thoroughly the powder flow in the dispensing nozzle.

Dry Powder Printing (DPP) or dry powder micro-feeding or fine powder dispensing is based on vibration, resulting from the ultrasonic vibration of a piezoelectric transducer, being used to assist flow. Over the recent past this DPP method has proved capable of handling fine powders. Pegna, who is a pioneer in this field, studied the possibility of multiple material deposition by creating a single layer of Portland cement [11] and spherical glass beads [12]. Santosa et al. demonstrated the influence of orifice diameters and under 100 µm particle sizes on flow behaviour under gravity through a hopper-nozzle [13]. Matsusaka et al. [14] investigated the microfeeding of fine powders in a capillary tube vibrated by a 20 kHz piezoelectric transducer. Takano and Tomikawa [15] developed feeding devices based on the excitation of a progressive wave in an ultrasonic transmission line. Li et al. [16] used an ultrasonic-based micropowder-feeding mechanism to form thin patterns of dry powders on a substrate which were subsequently sintered by a laser beam. Kumar et al. examined the concept of multiple dry powder deposition under gravity flow including low gas pressure-assisted flow and vibration-assisted flow and developed a model to predict the flow rate under gravity of the experimental powders [17]. Jiang et al. evaluated the flowability of nanoparticle powders [18] and developed a measurement system of powder flowability based on a vibrating capillary [19]. Yang and Evans [20, 21] presented the factors and mechanisms that were responsible for the initiation and cessation of flow in a vibration controlled dispensing system. Additionally, they identified the powder characteristics controlling powder handling so as to find effective metering and dispensing methods for shape and composition control for solid freeform fabrication [22]. Furthermore, they investigated the effects of acoustic frequency, amplitude, tube diameter, mechanical damping and particle size distribution on particle deposition from open capillaries subject to acoustic vibration [23]. They invented a discontinuous dispensing device using short pulses of ultrasonic vibration to dispense the dry powders in a drop on demand format [24]. Lu et al.[8, 25-27] studied dispensing mechanisms, drop size control, dose uniformity and different design of dispensing nozzles.

However, only a few studies have been carried out using ultrasonic vibration to dispense dry powders for MMAM [4]. The detailed mechanism of DPP has not been fully clarified and is needed for the technique to be a commercial success. The processing of fine powder in the micrometre size range has proved difficult [28, 29]. This is due to the feature size being driven by the size of the dispenser orifice, a smaller feature size resulting from a smaller diameter orifice. For the production of drops from sub-micrometre diameter size fine powders, the process is difficult to control reliably or sometimes powders cannot be dispensed because of their poor flowability. In this work, we have systematically investigated the effects of printing parameters on printing results which reveals the basic characteristics of our powder printing device. Furthermore, our study shows that dry powder printing, driven by ultrasonic vibration, can be exploited for fine powder printing of many types of powder materials.

<u>Materials and methods</u>

Materials

In this study, the selected powder materials were copper (Osprey Metals, Neath, Wales), solder (Sn63Pb37, IPS (Suzhou) New Materials Co. Ltd., China), 316L stainless steel (Osprey Metals, Neath, Wales), tungsten carbide (Sandvik, Conventry, UK), alumina (Al_2O_3, BA Chemicals Ltd., Buckinghamshire, UK), CoCr (Concept Laser GmbH, Lichtenfels, Germany), 420S45 stainless steel (Osprey Metals, Neath, Wales), glass bead (Whitehouse Scientific Ltd., UK), and Glass-filled Nylon (DuraForm® GF, 3D Systems Corp., USA) in the size range 14-72 μm and their details are shown in Figure 1 and Table 1. These materials were selected to cover metals, polymers and ceramics with different densities, particle sizes and particle shapes used in AM systems.

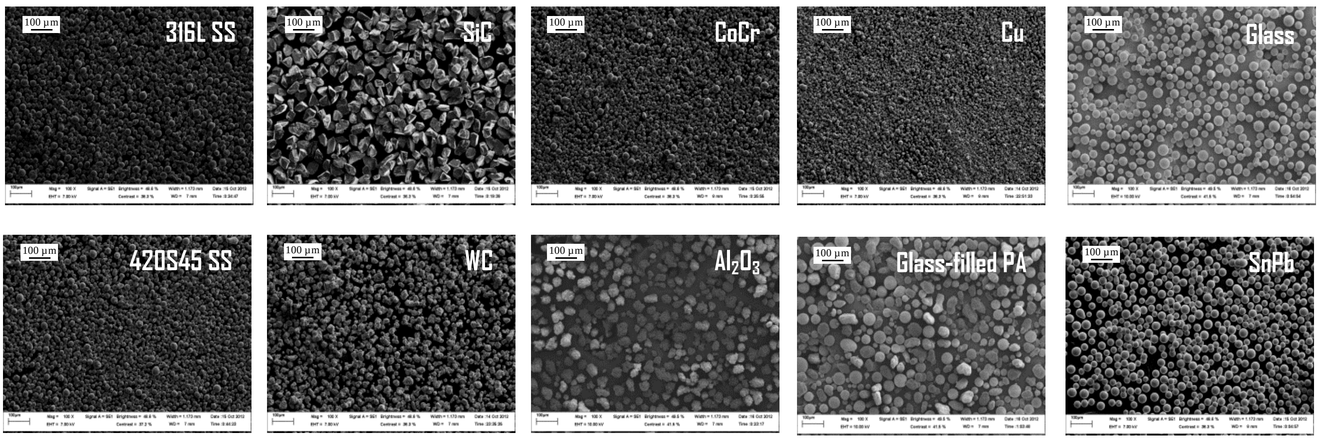

Figure 1 Scanning Electron Micrographs of the experimental powders.

The powders were analyzed to confirm that the size range was within specification by using a Malvern Mastersizer 2000 particle size analyzer. The particles were also characterized by a LEO 1455 VP Scanning Electron Microscope (SEM).

Table 1 Physical characteristics of the experimental materials.

Powder	Cu	SiC	Al2O3	Glass	CoCr	SnPb	316L SS	420S45 SS	WC	Glass-filled PA
D_{50} (μm)	14	54	52	41	18	35	32	20	35	72
Particle density(kg/m3)	8940	3220	3970	2300	8290	8400	7890	7740	15500	1490

Experimental setup

The experimental setup consists of a computer, an analogue waveform generator (NI 6733 DAQmx card, National Instruments Corporation Ltd. Berkshire, UK), a power amplifier (50w, Sonic Systems Ltd, Somerset, UK), a glass nozzle (Pasteur glass pipette) attached to a piezoelectric ceramic ring (SPZT8-100-50x20, MPI Co., Switzerland) by an adhesive epoxy (Araldite Rapid Syringe-Epoxy Extra Strong, Huntsman Corp., USA), Z column and X-Y table (Parker Hannifin, supplied by Micromech, Braintree, UK). The experimental setup is as shown schematically in Figure 2.

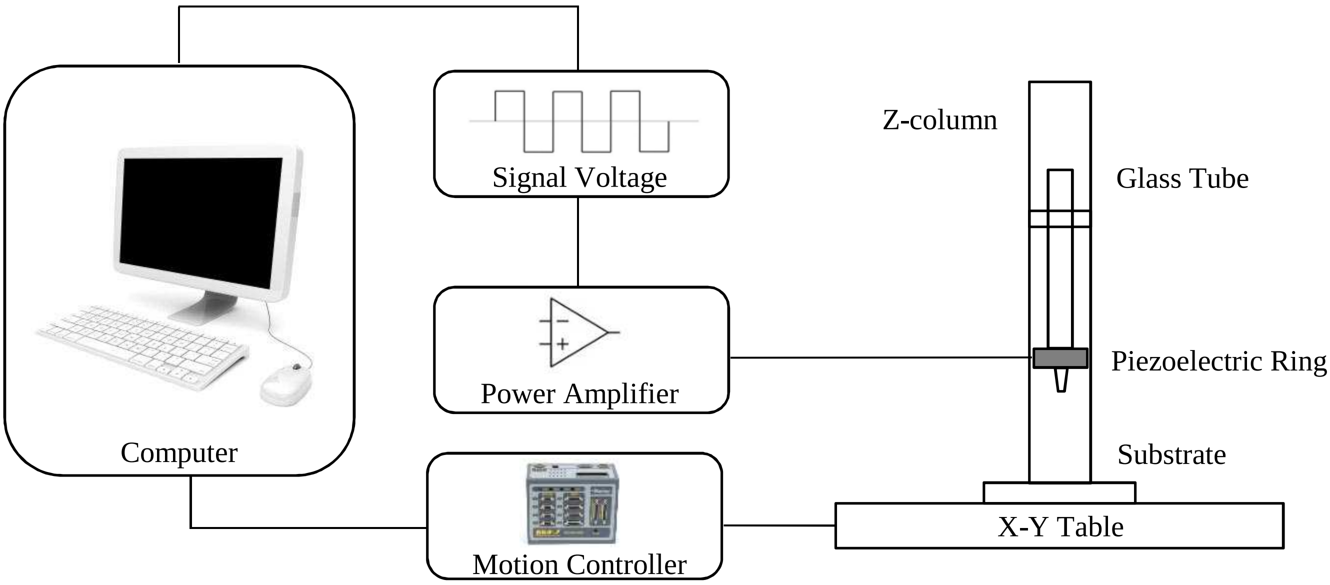

Figure 2 Schematic diagram of the dry powder printing system.

To capture images of the powder as it discharges in the experiment, a high- speed Photron Fastcam SA-1 (Photron Limited, Japan) camera attached to a c-mount adapter on a Leica Monozoom 7 (Leica Microsystem Inc., USA) macro lens was installed close to the dispenser.

Experimental conditions

The experiments were carried out under room conditions (23-28 °C and 36-45 % RH). As contaminants in the powder can reduce their mass flow rate from the dispenser and even clog the orifice a clean environment and sieving the powder before testing are essential. In this study, powders, which were kept in air tight packages, were sieved through a 100-micrometre sieve size before filling the dispenser, i.e. all particles dispensed passed through a 100-micrometre sieve size.

Results and discussions

Dispensing behaviour

The powder is dispensed by a vibration-assisted system using a glass nozzle as a funnel and a computer control system. Powder drops are discharged directly from the dispenser. Initially, particles form a stable dome structure across the orifice as shown in Figure 3. Powders are dispensed through the orifice by breaking the dome structure by activating a voltage signal pulse to the piezoelectric transducer attached to the dispenser.

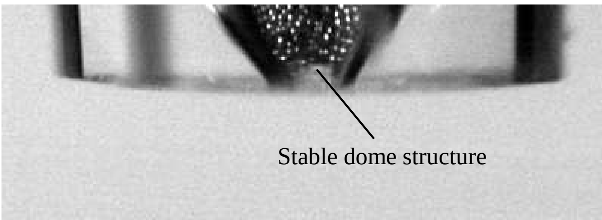

Figure 3 Dome structure of a fine powder inside the glass nozzle.

During dispensing, the vibration from the piezoelectric transducer transmits energy through the glass tube to particles around the dome structure and the result is to break the dome structure and so achieve flow of the powders. On switching off the vibrations, particle-particle and particle-wall friction lead to the formation of domes causing powder flow to arrest in the nozzle. Figure 4 shows the sequential images captured by a high speed camera at 0.01 second increments from the start of dispensing (B) to the cessation of dispensing (G) when the powder forms a new stable dome structure (H-J) inside the glass nozzle.

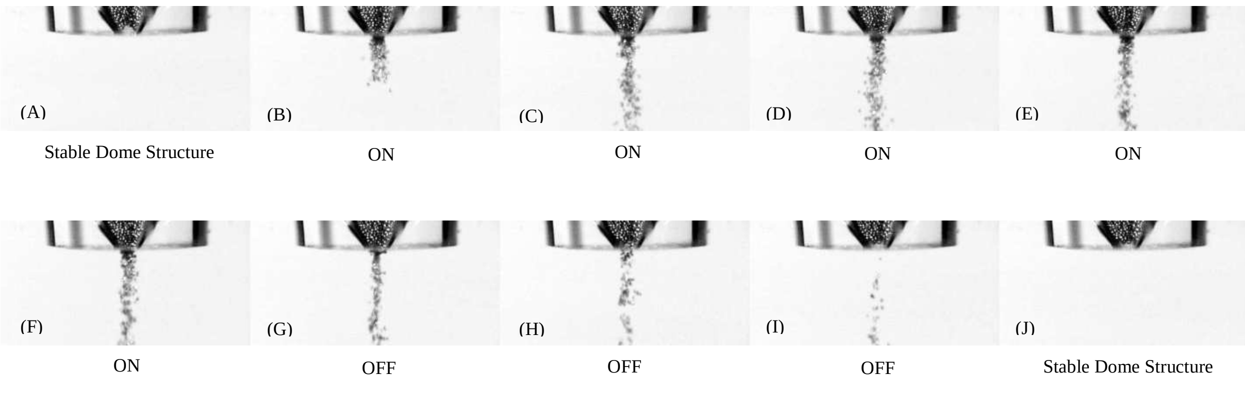

Figure 4 Sequence of images captured from the start of dispensing to the cessation of dispensing of a fine powder from the glass nozzle.

Printable materials

The ten experimental powders detailed in Table 1 were successfully discharged as can be seen in Figure 5. All of these results came from the same dispenser geometry, i.e. a 250 µm nozzle diameter with a nozzle angle of 75°. Throughout this study, the experiments were carried out at an applied signal voltage of 2 Volts, standoff distance of 200 µm and moving speed of 10 mm/s. Notably, the appropriate control of parameters for each experimental powder can improve markedly the deposited powder patterns.

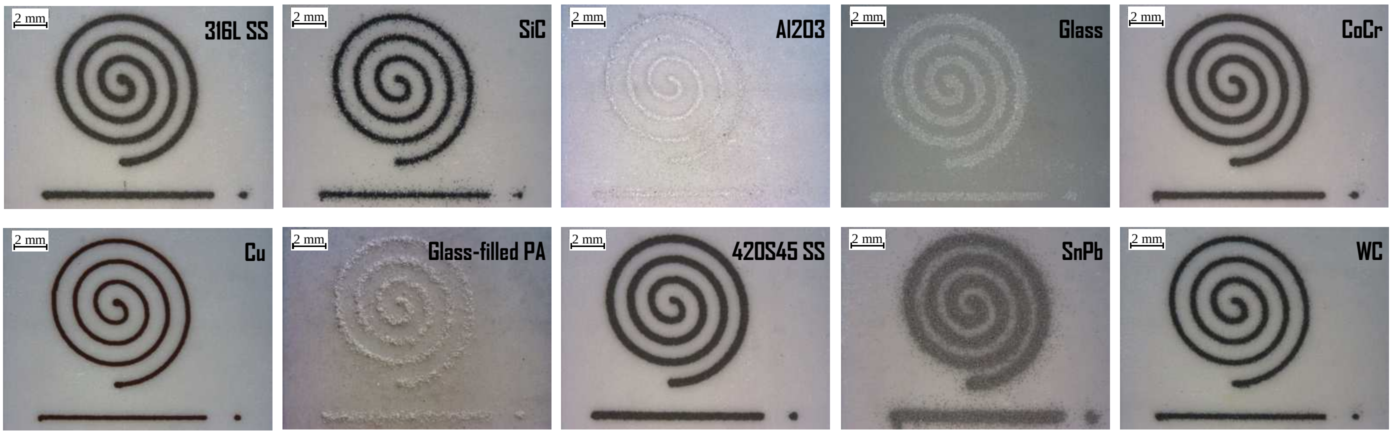

Figure 5 Single material patterns.

The quality of the patterns, which is characterised in term of continuity, consistency and fineness of the edge of the printing line produced mainly depends on the powder's flowability and the orifice size. Based on the particle's density and mean particle diameter all the experimental powders, except for copper and glass-filled nylon, fit into groups A and B of Geldart's classification presented in Figure 6, The copper powder and the glass-filled nylon are located in group C. Group A powders are ideal for conveying in sliding bed flow, Group B powders are easy to fluidize and they rapidly de-aerate while Group C powders are difficult to fluidize and are cohesive [30, 31]. Moreover, all of the experimental powders in Figure 1 do not agglomerate and have discrete particles. It may be concluded that in all cases, the powders used in this study are free-flowing materials or not extremely cohesive.

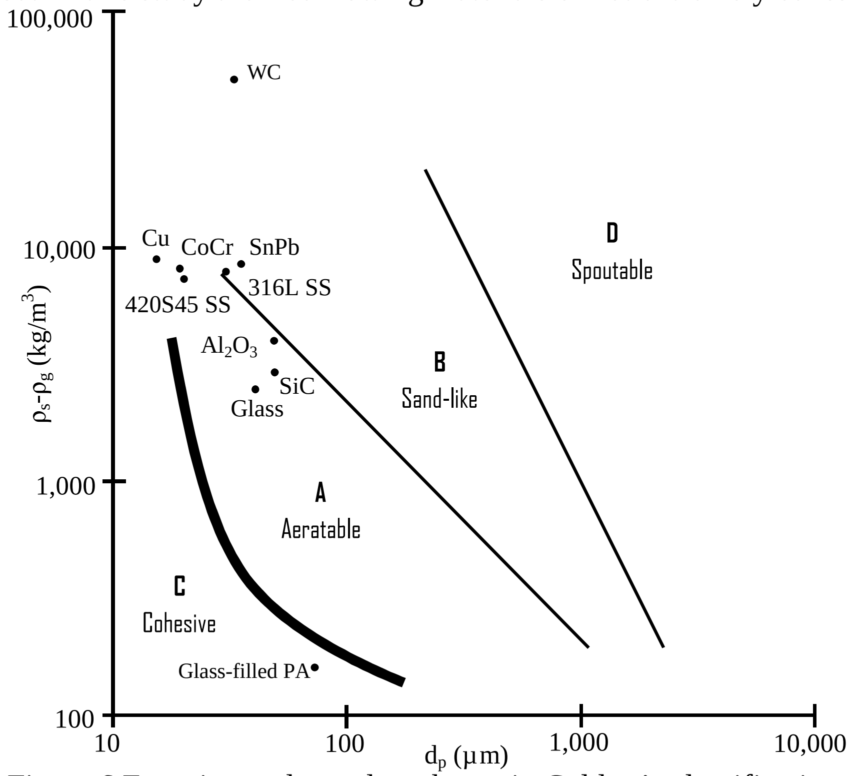

Figure 6 Experimental powders shown in Geldart's classification (ρ_s-solid density, ρ_g-gas density, d_p- mean particle diameter)

Printing of fine track width

The printing patterns are produced by CAD programs such as SolidWorks. The printing parameters of signal voltage, standoff distance and moving speed are programmable input via software. High precision stages are used to achieve x, y and z movement. The experimental studies found that high resolution depends on powder flowability, nozzle orifice geometry (nozzle diameter and nozzle angle), standoff distance and moving speed (the relative velocity between the substrate and the nozzle) as well as the signal voltage used to activate the piezoelectric transducer. Different parameters in the dispenser system need to be carefully adjusted for optimum results as the different powders have their own flow properties. A different adjustment of parameters can result in the feature sizes shown in Figure 7.

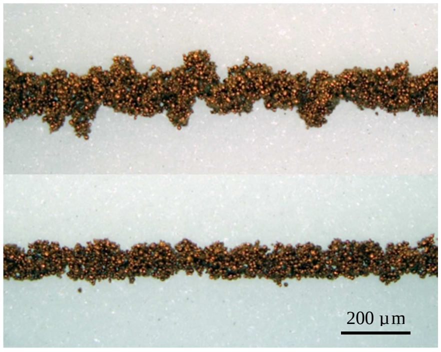

Figure 7 Patterns obtained from two printing conditions with the same nozzle diameter (70 µm) and the same signal voltage (2 Volts): (A) the standoff distance is 475µm, and the moving speed is 10 mm/s, (B) the standoff distance is 125 µm and the moving speed is 15 mm/s.

At present, the DPP printing device using an orifice diameter of 60 µm can realize a feature size down to 85 µm as shown in Figure 8. During the printing process the standoff distance of the deposition nozzle from the substrate was 150 µm, the moving speed was 5 mm/s and the signal voltage was 2 Volts.

Figure 8 Samples with a track width of less than 100 µm.

Nozzle diameter

Mass flow rate as a function of dispensing nozzle diameter was determined for the copper powder and solder powder of 14 µm and 35 µm mean particle size respectively. The nozzle diameters used were 110, 200, 250, 280, 320, 375 and 400 µm. The signal voltage was fixed at 2 Volts and the nozzle angle was 66°. Figure 9 shows the results of the mass flow rate for the two selected powders tested with this range of nozzle diameters. The mass flow rates increase with nozzle diameter. The results show that with the smallest nozzle diameters, the mass flow rates of the experimental powders are similar but they rapidly increase with increasing nozzle diameter. Throughout the range of these nozzle diameters, the solder powder has a higher flow rate (higher power law exponent) than the copper. This reflects the fact that a free-flowing powder such as the solder powder has higher flowability and thus greater mass flow rate than a cohesive powder such as the copper powder.

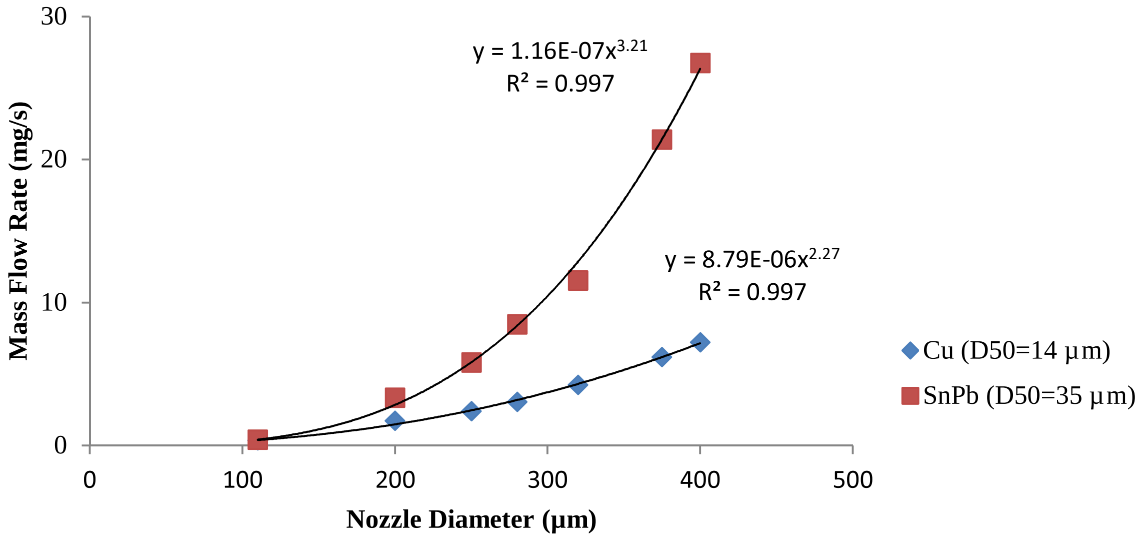

Figure 9 Mass flow rate as a function of nozzle diameter for copper and solder powder.

Signal voltage

The piezoelectric vibration enables powder printing to be achieved. The mass flow rate can be regulated by the vibration energy generated by the signal voltage, which controls the deformation amplitude of the piezoelectric transducer. Generally, when a greater voltage is applied the vibration amplitude increases. In our study a free-flowing powder, such as the solder powder, discharged as a spray of particles as shown in Figure 10 and the spray angle increased with increasing signal voltage. For a signal voltage of 0.15 Volts, the spray angle was less than 10º while for the signal voltage of 0.5 Volts and 2.0 Volts, the spray angle was around 30º and 90º respectively. The reason might be that the high vibration energy transmitted to the powder particles results in greater vibration of powder particles around the nozzle wall. As the particles exit the nozzle they hit the edge of the orifice and thus spread out. This effect is less when using a larger nozzle diameter or using a cohesive powder such as copper. Thus it can be seen that by choosing a suitable signal more uniform and consistent powder dispensing can be achieved and therefore more precise patterns produced.

Figure 10 Sequence of images obtained from a high speed camera at 0.05 second increments showing the successive stages of discharge of solder powders. The nozzle diameter is 250 µm.

Standoff distance

Standoff distance is the distance of the tip of the nozzle to the top of the substrate. From the previous discussion, it can be seen that powders normally spread out, the spray angle depending on the signal voltage. Therefore, the standoff distance should be as small as possible. However, the lower limit to standoff distance depends on the moving speed as the standoff distance must be sufficient to avoid powder blocking flow between the tip of the nozzle and the top of the substrate. Figure 11 shows the results of printing at different standoff distances. The track line at the 125-µm standoff distance results in the tip of the nozzle coming into contact with the powder resulting in compressing the printed line and might interrupt the powder flow at the outlet.

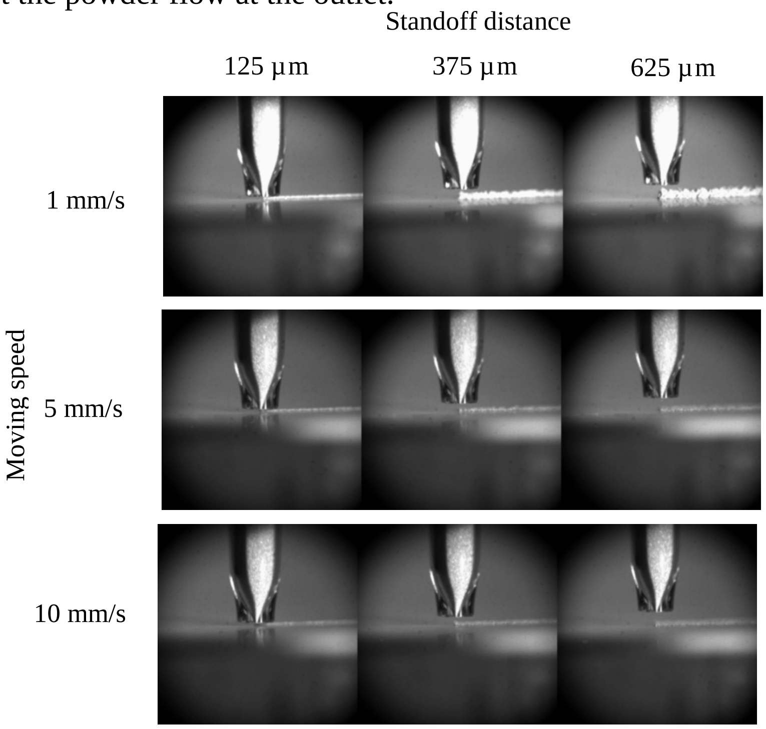

Figure 11 Sequence of images obtained from a high speed camera for copper powder dispensing with different moving speeds and standoff distances. The nozzle diameter is 250 µm.

Moving speed

Moving speed is the relative speed between the nozzle and the substrate. A fast moving speed can increase the printing speed of the process. However, the moving speed must not be so fast as to produce a discontinuity in the printed line. Figure 12 shows that copper printing with moving speeds of 20 mm/s and 25 mm/s cannot create complete printed lines. It indicates that the maximum moving speed in this test should be less than 20 mm/s.

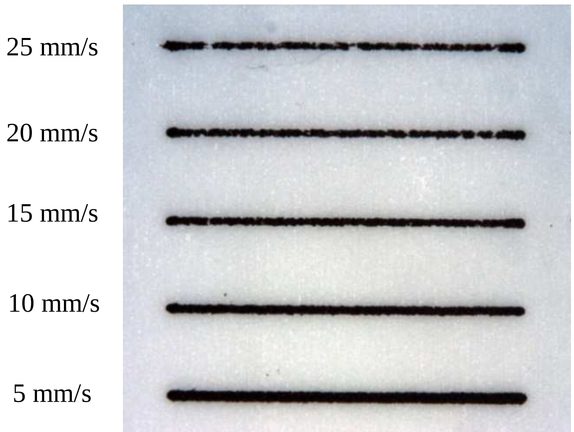

Figure 12 Printing results for copper powder obtained from different moving speeds. The nozzle diameter is 250 µm, the signal voltage is 2 Volts and the standoff distant is 200 µm.

Multiple material patterns

Figure 13 demonstrates the capability of printing multiple powder materials. Three sets of optimal parameter were used to produce a fine pattern. The pattern combines stainless steel, tungsten carbide and copper powder. A system consisting of three dispensers was installed on the z column and the x-y table was synchronised by the motor controller.

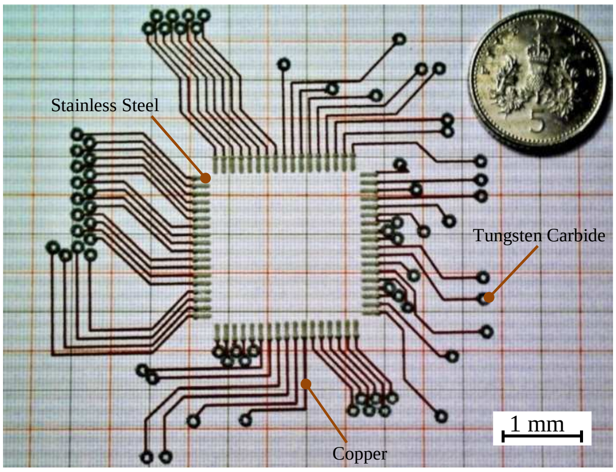

Figure 13 Multiple material pattern.

Advantages

This DPP technique can print various materials and little material preparation needs to be carried out. Using separate nozzles to deposit powder material in selective areas is an accurate, efficient and easy method which avoids contamination between materials. The device has few components resulting in less maintenance and an economical cost. Different materials can be printed simply by adding a new dispenser to the system. Utilising a nozzle based method, powder materials can be delivered between and within layers to make multi-oriented interfaces in a final part. It is believed that using a dry powder dispensing system integrated with current powder-based additive manufacturing systems, such as laser sintering, laser melting or binder jetting, would increase their ability to produce multiple material parts.

Limitations

A limitation of this device is that the process requires a small standoff distance to provide high resolution and to avoid spreading due to the spray effect. Additionally, accidental vibration from the environment, e.g. movement of the x-y table, can affect the controllability of powder dispensing. However, this can be overcome by mounting the device in a system with smooth movement and adequate damping. Furthermore, the dispenser must be installed vertically because the device combines vibration and gravitational force to discharge material.

Conclusions

In this paper, a novel Dry Powder Printing (DPP), based on an ultrasonic dispensing device where powder flow can be regulated by controlling input to the piezoelectric transducer, is introduced. The development of this novel DPP method would allow the layering of high quality multiple material patterns. By programming the print heads, this powder printing technique can achieved selective area deposition of different dry powder materials using ultrasonic activation without sophisticated material preparation. The novel device allows the deposition of a wide range of powder materials. This device represents a step forward in realizing multiple material objects in MMAM systems.

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