Advanced deposition techniques for freeform fabrication of metal and ceramic parts

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Abstract

Two newly invented deposition techniques for the freeform fabrication of metal and ceramic parts are presented. The first deposition technique studied is one that can deposit variable sizes of filaments in a controlled manner. The second technique consists of layer deposition using an adjustable planar nozzle to generate layers directly. Laboratory scale apparatus has been built to study the behavior of filament and layer formation of these two techniques. Experiments are conducted in typical operation ranges. Analytical solutions are also developed to parametrically study the effects of changing major operational parameters as well as to provide necessary information for designing the apparatus. All results indicate that the analytical predictions agree very well with the experimental observation. Finally, recommendations on the future development of these two techniques are given.

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Introduction

Freeform fabrication technology does not require pre-formed mandrels or tooling; instead, it builds physical objects directly from computer graphical data. This type of technology is also known as layer manufacturing, since it constructs the three-dimensional object layer by layer (Jacobs, 1992; Beaman *et al.*, 1997). The technology has proved that it can help to rapidly provide feedback on design concepts, discover inconsistencies in the design, modify the design, and eliminate inconsistency before fabricating the design. This greatly reduces the production cycle time, and tremendously contributes to quality, competitiveness, and reductions in maintenance cost.

Because most of the commercially available freeform fabrication techniques can only handle materials at relatively modest temperatures, almost all prototyping parts are made of low-temperature polymeric or oligomeric hydrocarbon materials. These low melting temperature materials have only moderate strength. For many engineering applications, however, the strength of the prototypes is critical. To cope with this shortcoming, two deposition techniques presented in this paper have been developed for layer manufacturing of high-strength metal and ceramic parts. Both techniques are also much simpler and faster than the current freeform fabrication technology which can further speed up the product launch and drive down the cost and time to market for the new product. The first technique is called the Adaptable Filament Deposition (AFD), and is capable of depositing variable sizes of filaments in a controlled manner. The second is the Planar Layer Deposition (PLD) which uses an adjustable planar nozzle to deposit layers directly.

The AFD can produce filaments with desirable diameters which are deposited and solidified into a layer having a desirable

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thickness (Tseng, 1998). In freeform fabrication, the ability to have a variable layer thickness allows for more efficient and accurate fabrication of physical components. To develop an appropriate control strategy for this process, the filament formation behavior has been studied analytically based on the principles of momentum and energy conservation. An experimental filament generator has also been built and experiments have been conducted at a wide range of filament forming conditions. The experimental results have been used for refining the system design as well as for verifying the analytical predictions.

In PLD, a continuous liquidus sheet is formed by an adjustable planar nozzle, then passes through a pair of rollers for pressing, cooling, and leveling (Tseng, 2000). The sheet is then deposited on to a position controllable substrate to form the desired shape. Almost all freeform fabrication techniques currently commercially available, including stereolithography, selective laser sintering, three-dimensional printing, shape deposition modeling, fused deposition modeling (FDM), and ink jet printing (Jacobs, 1992; Beaman *et al.*, 1997) are based on a Raster or directional scanning procedure, also known as point-by-point fabrication (Jacobs, 1992). These systems build a single point at a time, and consequently, one scan only forms one line. On the other hand, the PLD technique uses an adjustable planar nozzle for the formation of variable wide semi-solidified sheets for making metal or ceramic parts. Using the PLD system, one straight scan, instead of the lengthy reciprocating Raster scanning, can build a complete or partial layer, depending on the geometry of the part. A prototype PLD system has been built to study the layer-forming behavior. Experiments are conducted to provide the required information for improving the current system design as well as for verifying the analytical prediction.

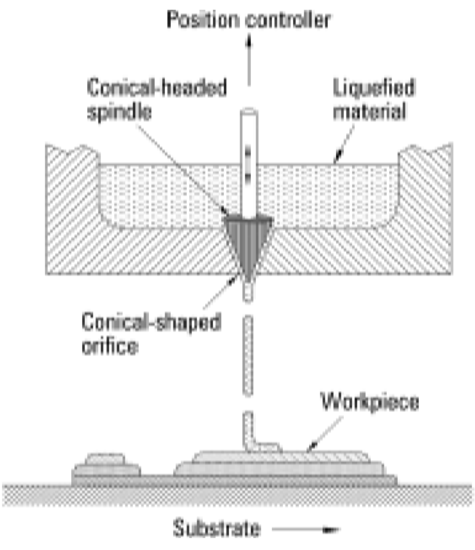
Adaptable filament deposition technique

The use of liquid-phase filament deposition has emerged as one of the major freeform fabrication technologies for forming three-dimensional solid components. The most widely known system is the FDM system developed and commercialized by Stratasys (Beaman *et al.*, 1997). The FDM system uses a resistively heated delivery head to melt thermoplastic wire-like filaments. Since this delivery head is x-y position controlled, the semi-molten filament can be deposited to the location where the object is to be fabricated. In this way, a thin layer of the required contour can be formed and a three-dimensional component can be built layer by layer upward from a substrate. Since the FDM system is equipped with a head of fixed diameter thus the output filament is limited to a constant size, i.e. the layers formed are of a constant thickness. In layer manufacturing, the layer thickness is often determined by the allowable limit of the aliasing or "stair-step" error that is caused by approximating angled surfaces with stacked layers of materials (Suh and Wozny, 1994). As a result, to improve aliasing, the filament deposition rate would decrease accordingly. As such, the FDM system becomes inadequate for making large-scale or high precision components.

Adjustable filament nozzle

The AFD system currently studied addresses this problem by utilizing a special nozzle, an adaptable circular nozzle able to form variable circular cross-sections of filaments and, in turn, to deposit variable thickness layers. The adaptable circular nozzle consists of a conical-headed spindle and a matched conical-shaped orifice (Lee and Tseng, 1998). As shown in Figure 1, by moving the conical spindle head

Figure 1 A schematic of adjustable circular nozzle



vertically with respect to the orifice, the amount of molten flow that passes through the nozzle can be regulated. The material flow follows the contour of the conical head to form a circular jet, which is then cooled by the ambient environment to become a filament having a diameter proportional to the amount of flow exited. As a result, filaments with a wide range of sizes can be obtained.

In fact, when the spindle is completely withdrawn from the nozzle orifice, there is no flow constriction and the effective nozzle diameter is the actual diameter of the orifice itself. When the conical spindle head seats in or touches the mating orifice, the material flow is completely impeded and no filament is generated. With this ability, the adaptable nozzle can generate only the wanted filaments to be deposited into the location where the object is to be formed (Tseng, 1998). A separated deposition selection system to distinguish the wanted from the unwanted filaments becomes unnecessary, and no recycling is needed for the unwanted filaments. Minus a separated deposition selection device, the complexity of the AFD system is greatly reduced.

Apparatus

A laboratory scale system has been designed and built for studying filament formation behavior. The system consists of a filament generator equipped with an adjustable nozzle, a deposition chamber, and associated controlling and monitoring systems as shown in Figure 2. A liquefied circular jet ejected by the generator is solidified into a series of filaments and disposed within the deposition chamber with, preferably, a PC-based system for monitoring and controlling the filament formation and deposition process. The hardware of the AFD system, in many respects, is similar to the conventional droplet deposition system (Orme *et al.*, 1996; Priest and Smith, 1997; Tseng *et al.*, 1999).

In the present system, the nozzle is adjustable while that of the droplet deposition process is fixed. The system is also equipped with many sensors for measuring pressure, velocity, and temperature, as well as video imaging. The slant angle and exit diameter of the conical-shaped orifice (or the conical-shaped head) are 10 degrees and 1.5-mm, respectively. The spindle of the nozzle which is regulated by a manual positioning device having 25-µm precision is mounted on top of the container.

Results

Experiments were first conducted to study the relationship between the position of the conical-headed spindle and the dimension of filament generated. Three types of material, water, wax, and Wood's alloy, were selected for the experiment. The Wood's (soldering) alloy is chosen for the building material while a wax is selected for the supporting material. In processing, the building material is only deposited to the location where the object is to be formed. The lower melting-temperature supporting material is deposited adjacent to the building materials to serve as a support structure during forming. Since the complementary material has a much lower melting temperature, it can be easily removed after completing the deposition process, leaving only the fabricated part.

In experiment, the temperature in the crucible was heated to a pre-set value: 355 K for wax and 366 K for Wood's Alloy, while water is conducted at room temperature. The pressure is then applied in the crucible and the jet is ejected through an opening of the desired size at the base of the crucible. The opening of the nozzle is adjusted by moving the conical-head spindle. Both the ejecting pressure and liquefied flow temperature can be controlled within 1 per cent of the measurement accuracy. For each experiment, the ejection pressure and material temperature are held constant and the amount of flow ejected and the associated time are recorded. By providing the specific weight or density of the liquefied material, the corresponding nozzle velocity can be estimated. The forming of the filament jet was monitored and recorded by a high-speed video camera. The diameter of the filament jet was examined by magnifying the video imaging to yield a measurement reliability of 10µm.

Experimental results were obtained for 20 vertical spindle positions; the correlation between the effective diameter (d_{eff}) of the adjustable nozzle and the actual filament diameter (d_f) was studied and plotted in Figure 3. Here, the effective diameter d_{eff}

Figure 2 Laboratory-scale adjustable filament deposition system

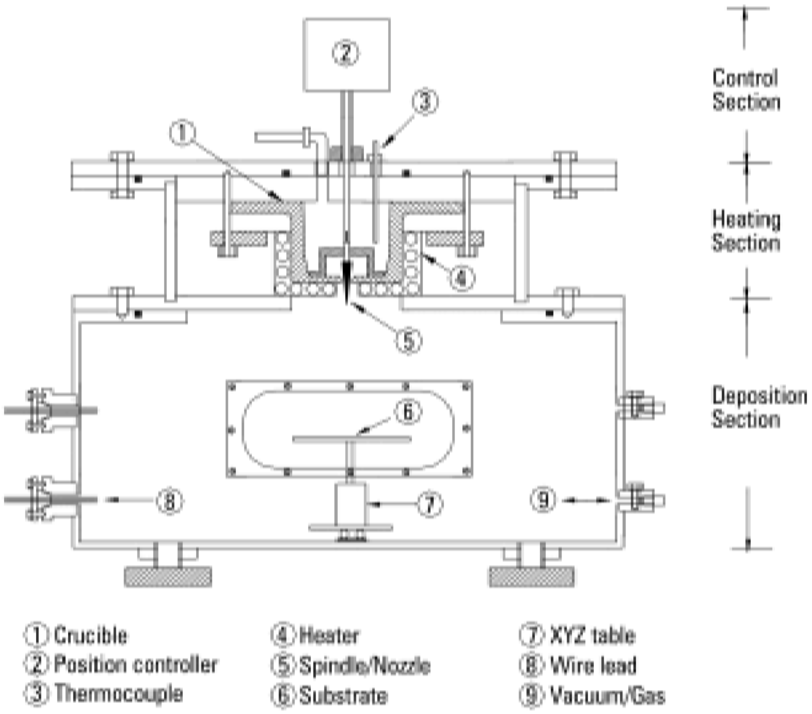
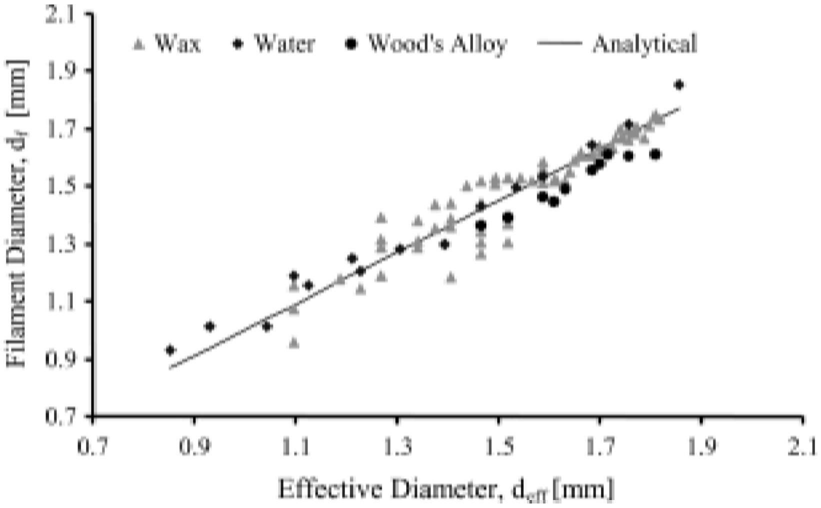
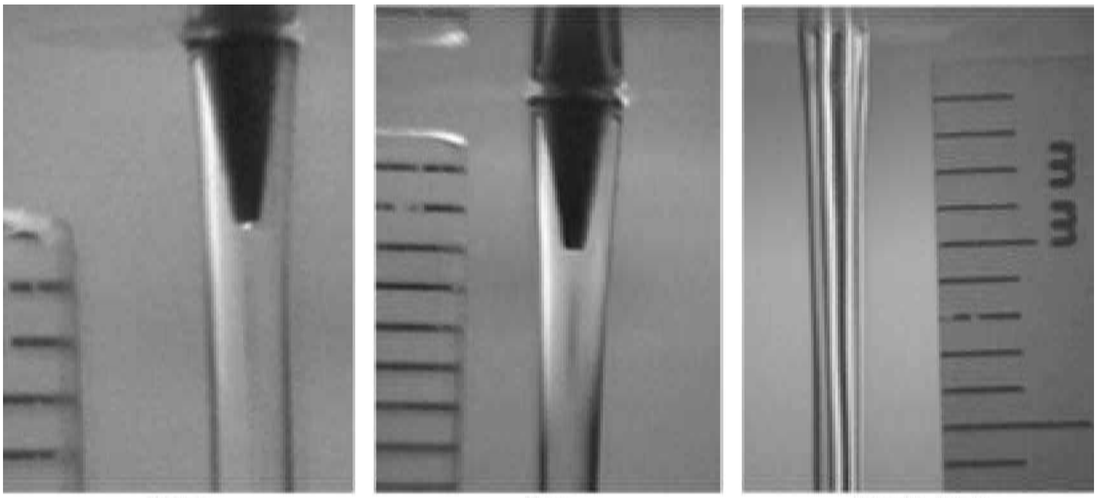


Figure 3 Relationship between effective nozzle diameter and filament diameter



equals $(d_o^2 - d_i^2)^{1/2}$, where d_o is the diameter of the conical orifice at the exit section and di is the diameter of the conical spindle head corresponding to the exit section; d_i changes according to the vertical position of the spindle. The filament diameter was measured at the location 10mm below the nozzle. It is to be noted that because of the effect of the gravity force, the falling speed of the filament jet is faster and the filament diameter is smaller, as the flying time increases. The 10mm deposition distance selected here is the minimum flying time required to partially solidify the filament. Figure 4 includes pictures of stable jets emanating from the spindle/nozzle for water, wax and Wood's alloy. The contour of the jet is smoothly contracting from the nozzle downward from the flow. In the figure, Re is Reynolds number equal to $\rho U_0 d_{eff}/\mu$, where ρ and μ are, respectively, the density and viscosity of the material considered and U_0 is the nozzle velocity. The specific values of the physical properties for the materials considered can be

Figure 4 Filament formation near adjustable nozzle region for different materials



Water
d_{eff} = 1.533mm
Re = 1844

Wax
d_{eff} = 1.465mm
Re = 111

Wood's Alloy
d_{eff} = 1.305mm
Re = 11207

found in the paper by Tseng, Lee, and Zhao (1999) and are summarized in Table I.

As shown, the concept of the adjustable nozzle is indeed feasible, whereby changing the vertical position of the spindle, the filament diameter (d_f) can be adjusted. Moreover, the relationship between d_f and d_{eff} (or the spindle position) is quite linear and the linear relationship will greatly simplify the required control software developed for the system considered.

The experimental correlation also agrees very well with the analytical predictions. The analytical solution used in comparison is obtained based on the principles of momentum and energy conservation (Fox and McDonald, 1985; Tseng *et al.*, 1999). Experiments have been conducted at a wide range of filament forming rates; the corresponding Reynolds numbers ranging from 50 to 5000 have been studied. All results indicate that the filament jets generated were very stable and filament sizes can be controlled according to the theoretical predictions.

Table I Material physical properties

	Water (295 K)	Wax (355 K)	Wood's alloy* (366 K)
Melting temp., T_m [K]	273	336	347
Density, ρ [kg/m^3]	999	773	9240
Viscosity, μ [Pa-s]	1.07×10^{-3}	4.6×10^{-3}	2.1×10^{-3}

Notes: *Data calculated by atomic weight method based on Wood's Alloy component: Sn12.5/Pb24.95/Bi50/Cd12.5/Ag0.5 (http://www.sra-solder.com/pastesp.htm)

Planar layer deposition technique

The PLD system comprises a multi-cylinder container equipped with adjustable planar nozzles, one or more pairs of rollers for pressing, cooling, and leveling, and a deposition chamber containing a position controllable substrate, as shown in Figure 5 (Tseng, 2000). Each cylinder of the container is equipped with a heating and a pressure control device. The cylinder holds and liquefies a charge of a forming material. The forming material can be polymers, metals, or powders bounded with polymers. Each type of material is separately handled by a cylinder. The part can be built layer by layer as guided by computer software until it is completed.

Apparatus

A laboratory single-cylinder container managing one type of material has been designed and built as shown in Figure 6. To prevent the oxidation of the forming materials, the environment of the container is protected by a non-reactive gas, typically either nitrogen or helium. Pressure can be applied to the surface of the molten material by a piston or by a pressurized inert gas, thus forcing the material to flow out of the adjustable nozzle, resulting in the formation of a continuous planar sheet or layer of uniform thickness.

The fluidized sheet formed by the adjustable planar nozzle passes through single or multiple pairs of counter-rotated rollers for cooling, pressing, and leveling. It is then

Figure 5 A schematic of planar layer deposition system

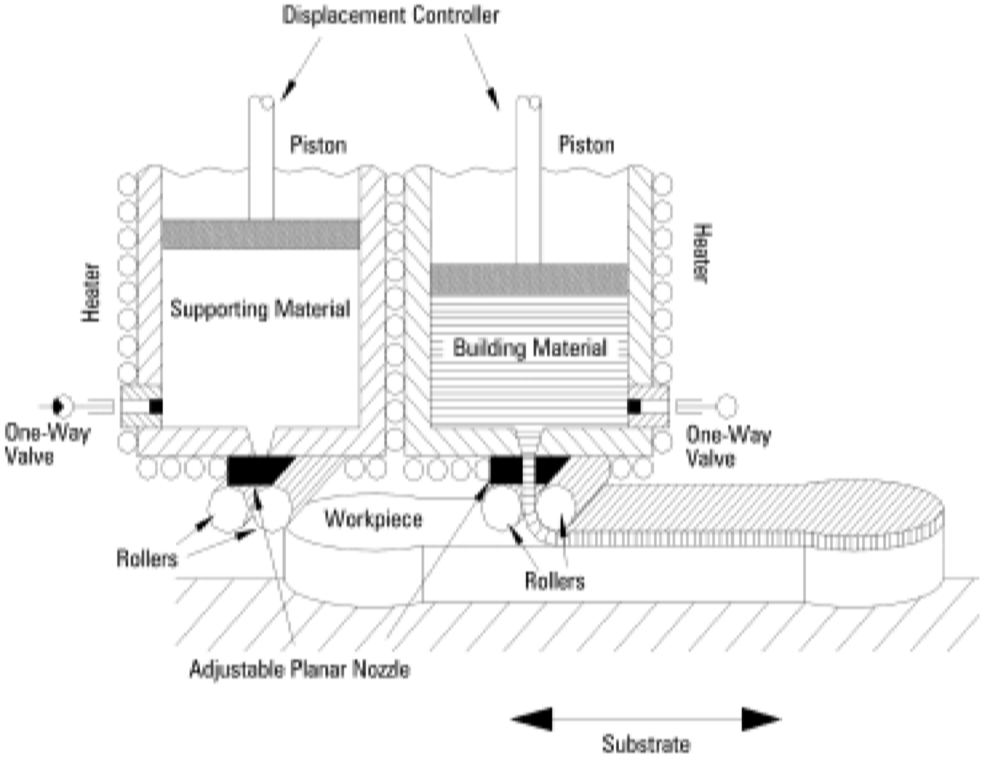
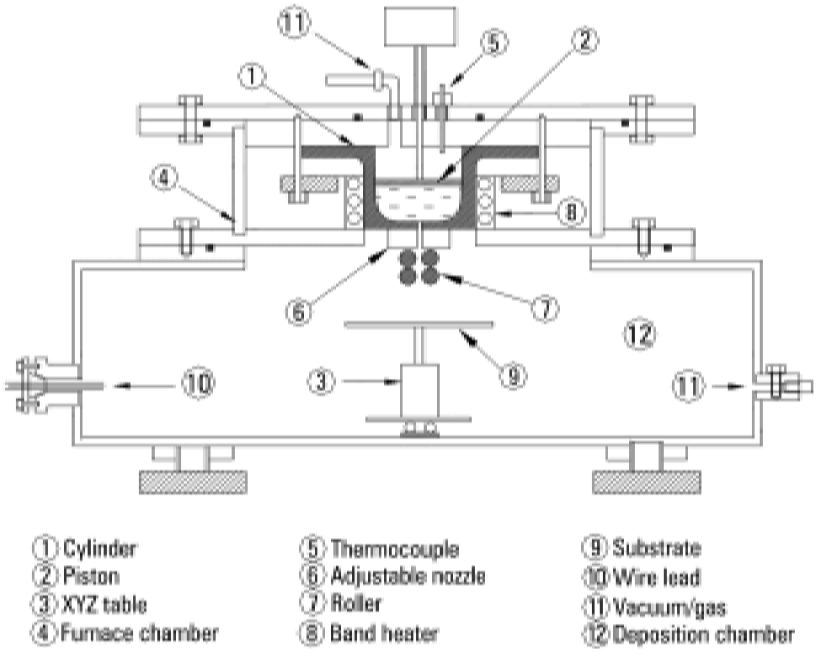


Figure 6 Laboratory-scale planar layer deposition system



deposited and fully solidified on the position-controllable substrate. Both the rollers and controllable substrate are located in the deposition chamber. The rollers are made of high-temperature, high-wear resistant alloys and dragged by the contact friction between the roller and semi-solidified sheet. The rollers can also be driven by motors, but their speed should be synchronized with the deposition speed.

The rollers first act like withdrawal or cooling rolls in a continuous casting process (Zou and Tseng, 1992) for freezing the fluidized polymer/ceramic sheet. At the same time, the rollers resembling the compaction rolls in a powder rolling process (Reed, 1988) increase the density and strength of the semi-frozen polymeric sheet. The use of rollers for leveling is extremely important because it directly affects the final dimensions of the freeformed product. If the pressing task is important, the rollers can be strengthened by a pair of backup rolls. Also, to enhance their cooling effectiveness, the rollers can have drilled passages to allow the coolant to pass through, similar to those used in a calendering process (Tseng *et al.*, 1993).

The position controllable substrate is centered on a motorized positioning table capable of translating in all three Cartesian axes with micrometer resolution. The positioning table consists of a xy assembly with an independent z-axis movement driven by the stepping motors supplied by Industrial Device Corp. of Navato, CA. The table is controlled by a personal computer through an installed AT6400 motion control card provided by Parker Hannifin Corp. of Harrison, PA. Furthermore, the positioning table is implemented with proximity sensors to limit the travel of the table and two sensors for each axis are placed. These sensors are for preventing unexpected accidents when giving wrong motion commands to the system. When the table tries to pass on this sensor, the sensor activates and the AT6400 indexer forces the stepper to be shut down.

Inputs from the computer to the position controller are governed by software that accepts three-dimensional data in CAD-type formats, slices the data into appropriate layers, and then properly positions the substrate beneath the semi-solidified sheet to form each layer. The control software is developed in-house and written in Microsoft Visual Basic 6.0 for sending a motion command to the control card with an aid of a file, called Dynamic Link Library, provided by the vendor, Parker Hannifin Corp.; the Library includes several functions readily available to send and receive motion codes in Visual Basic environment.

Pressure control and analysis

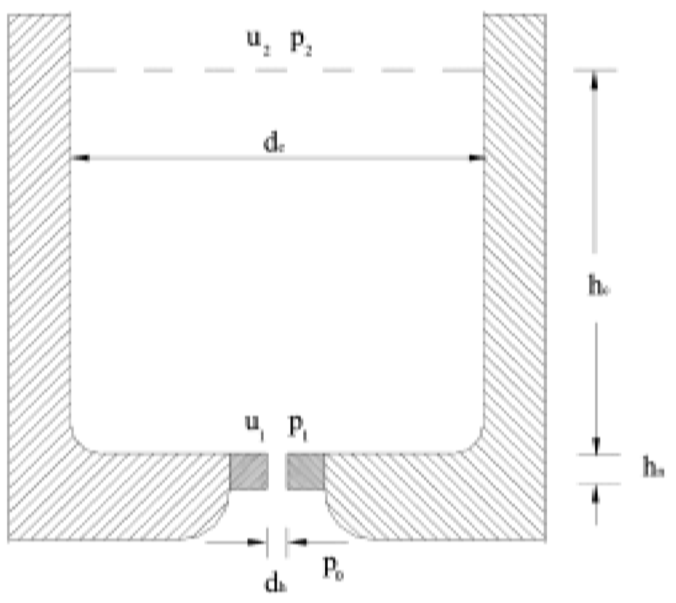
The speed of the layer formation or deposition is dictated by the flow velocity at the planar nozzle. The flow velocity at the nozzle can be controlled by the applied pressure in the container. Since the width of the planar nozzle varies according to the geometry to be deposited, the pressure is required to be regulated to keep the nozzle flow velocity constant to maintain uniform layer deposition on the substrate. An analytical relationship among the applied pressure, flow nozzle velocity and corresponding opening of the planar nozzle has been developed for better control of the layer formation and deposition. For a crucible geometry shown in Figure 7, based on the principle of energy conservation, the normalized basic equation of the flow considered can be found (Fox and McDonald, 1985):

$$\Delta P = U_o^2\left(\frac{\alpha_o}{2}-\frac{\alpha_2}{2}D_n^4+\frac{K_c}{2}\right)+ U_o\left[32\mu^*\left(H_cD_n^2+\frac{H_n}{D_n^2}\right)\right]-(H_c+H_n)\quad(1)$$

where ΔP is the normalized pressure difference equal to $(p_2 - p_O)/(\rho g d_c)$; U_O is the normalized nozzle velocity equal to $u_O/(g d_c)$; μ' is the normalized viscosity equal to $\mu/(\rho g^{1/2} d_c^{3/2})$; D_h is the normalized nozzle opening equal to d_h/d_c; H_c and H_n is the normalized elevation heads of the crucible and nozzle equal to h_c/d_c and h_n/d_c, respectively; α_O and α_2 are the kinetic energy coefficients of flow in the crucible and nozzle, respectively; and K_c is the contraction loss coefficient from the crucible to nozzle. Here p_2 is the applied pressure, p_O is the ambient pressure, μ is the flow viscosity, ρ is the flow density, g is the gravity acceleration, and d_c is the crucible diameter.

Since the width of the planar nozzle varies, the nozzle opening changes accordingly. In the present analysis, the hydraulic diameter of

Figure 7 Geometries of crucible and adjustable planar nozzle



the nozzle opening, d_h, is selected to quantify the cross-section area changes of the planar nozzle. The contraction loss coefficient, K_c, represents the head loss for flow through the sudden area contraction from the crucible to the nozzle and is proportional to D_h^2. Based on the geometry of the present crucible design, D_h should be much smaller than 0.1 and the coefficient K_c approaches to a constant of 0.5 based on the correlation provided by Fox and McDonald (1985).

In equation (1), the pressure head losses due to the viscous effects in the nozzle have been taken into account. The kinetic energy coefficient, α_o and α_2, are dependent on the velocity profile in the crucible and nozzle section. Since the velocity profile at the entrance region is quite flat, a power-law profile having the seventh power is assumed for the velocity at the crucible and nozzle. Following the formula provided by Fox and McDonald (1985), the kinetic energy coefficients, α_o and α_2, can be found to be 1.05.

The algebra equation of equation (1) can be easily solved and the normalized nozzle velocity, U_o, can be explicitly expressed by:

$$U_0 = \frac{-B + (B^2 + 4AC)^{0.5}}{2A} \tag{2}$$

where

$$A = \left(\frac{\alpha_0}{2} - \frac{\alpha_2}{2} D_n^4 + \frac{K_c}{2}\right),$$

$$B = 32\mu^* \left(H_c D_n^2 + \frac{H_n}{D_n^2}\right),$$

and

$$C = \Delta P + H_c + H_n$$

For the better control of the layer forming process, the relationship among the applied pressure (ΔP) and the flow nozzle velocity (U_O) and planar nozzle opening (D_h) is studied here. Based on the geometry of the laboratory apparatus shown in Figure 7, the effects of the applied pressure on the flow nozzle velocity at several typical nozzle openings are plotted in Figure 8. The data used in the calculation include the diameter of the crucible (d_c = 100mm) and the elevation heads of the crucible (h_c = 100 mm) and the nozzle (h_n = 0.25 mm). Figure 8 shows that, as expected, the nozzle velocity grows as the applied pressure increases. However, it is surprising to find out that by varying the nozzle opening or the width of the planar nozzle, the effects on the nozzle velocity are negligible for the range considered.

The detailed information on the influence of the planar nozzle opening on the applied pressure at typical nozzle velocities can be found in Figure 9. If D_h is larger than 0.001, the effect of the nozzle opening indeed can be negligible. This means that for an 100mm diameter crucible, as long as the hydraulic diameter of the planar nozzle is larger than 100μm, the effect of changing the width of the planar nozzle can be negligible. For making typical engineering parts, the hydraulic diameter of the planar nozzle should be hardly smaller than 100μm. As a result, the insensitivity of the size of nozzle opening on the pressure could provide a more stable environment for control of the layer formation, since the applied pressure can be used to directly control the nozzle velocity or layer formation speed, without the interference of the effect by changing the nozzle size.

Because of its low melting temperature, Wood's alloy is a popular metal used in freeform fabrication research and its material properties have been used in calculating the data presented in Figures 8 and 9. In fact, the material properties only affect the term μ' in either equation (1) or equation (2). If the properties of μ and ρ of other materials, including wax and water shown in Table I, are used in the calculation, the corresponding results are similar to those presented in Figures 8 and 9 and the differences are less than 3 per cent for the conditions considered. As a result, the information shown in Figures 8 and 9 can be considered as a general case suitable to all kinds of materials involved.

The correlation between the nozzle velocity and the ejection pressure predicted in Figure 8 has also compared with the experimental observation for both the wax and Wood's alloy cases; the analytical predictions agree excellently within 6 per cent with the experimental results for the conditions considered. Consequently, the analytical prediction can be concluded to be very reliable and can be adopted to provide the guidance for control of the layer formation in the planar layer deposition technique.

Adjustable nozzle

The present design of the adjustable planar nozzle consists of two slotted plates equipped with a motorized position controlling device

Figure 8 Relationship between nozzle velocity and applied pressure

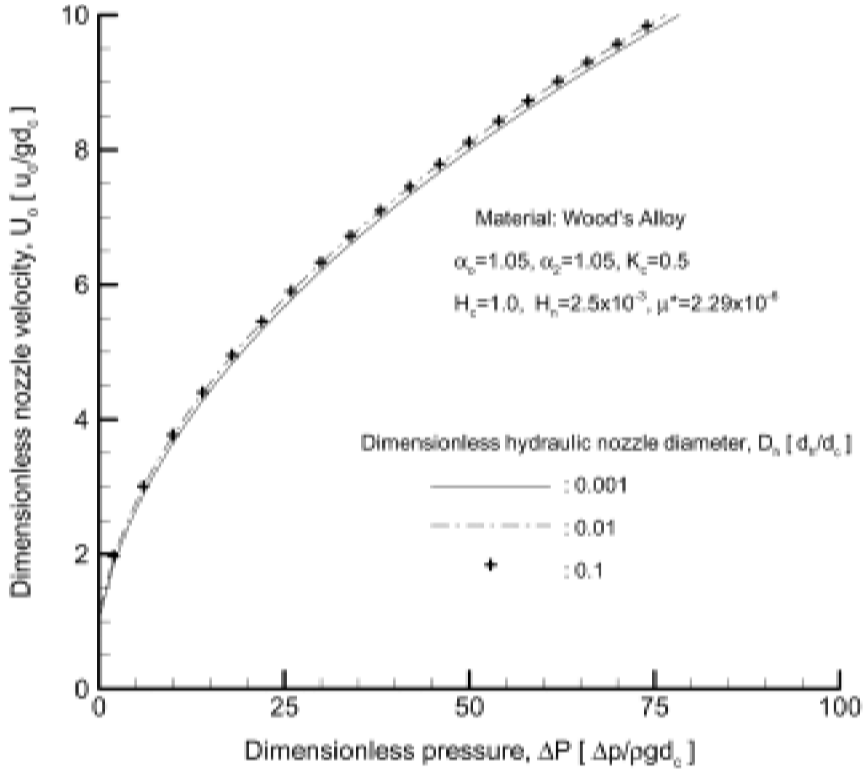
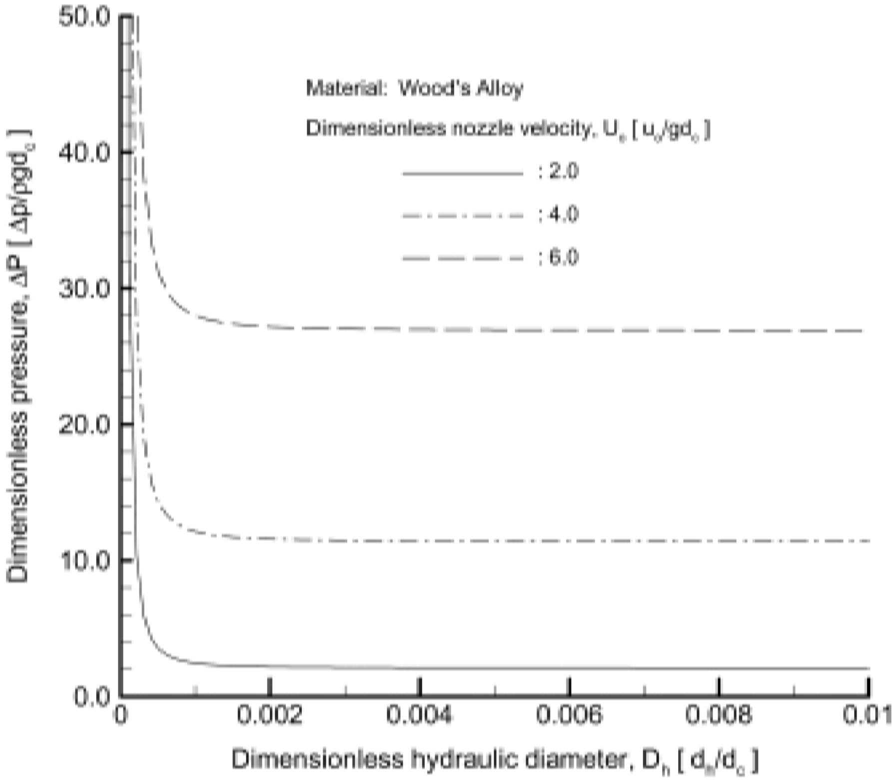
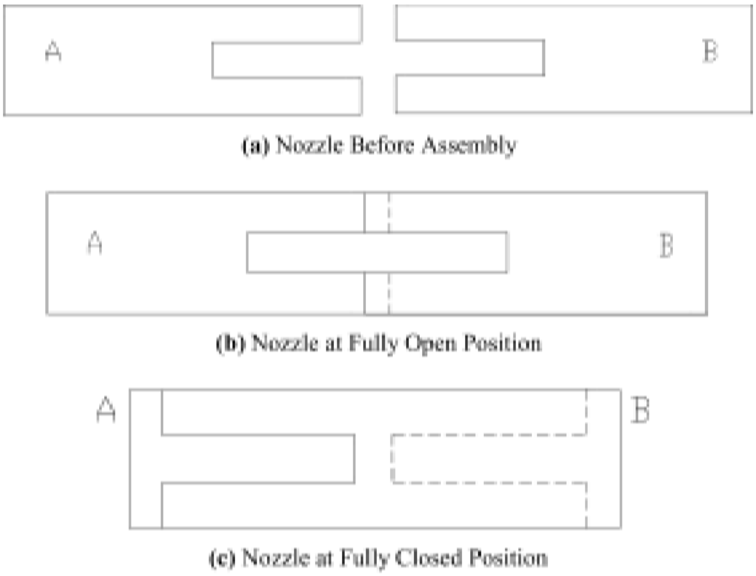


Figure 9 Effects of nozzle opening (hydraulic diameter) on applied pressure



of micrometer resolution. During operation, the two slotted plates are assembled so that they can be slid over one another as shown in Figure 10. Under such an arrangement, the width of the nozzle opening can be adjusted, as needed, from fully open (Figure 10b) to completely closed (Figure 10c). A container equipped with this type of adjustable planar

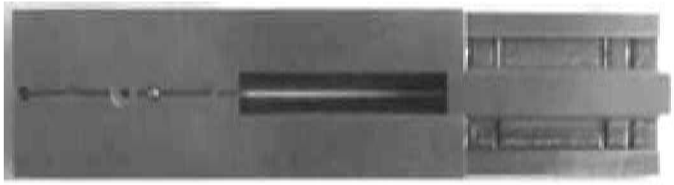
Figure 10 A schematic of adjustable planar nozzle



nozzle forms a semi-solidified sheet of desirable width which is deposited on a position controllable substrate and undergoes rapid solidification within the deposition chamber as shown in Figure 6.

In the present design, the planar nozzle opening is 0.5 mm high and its width can be adjusted between 0 and 50 mm. The top and bottom views of the assembled nozzle are shown in Figure 11a and 11b, respectively. As an example, for a 150mm wide part, three scans are needed to form a whole layer. Eventually, a system that integrates several planar nozzles will be designed, so that only one scan can cover a much wider region. It is to be noted that the layer thickness is equal to the opening height, 0.5 mm, and represents the accuracy of the freeformed part. For a more accurate part, the opening height should be on the order of 50 μm. The nozzle shown in Figure 11 has been used to deposit different types of layers. Some layers formed by this nozzle for ABS polymer and low melting-temperature wax are shown in Figure 12a and 12b, respectively. Figure 13 shows a typical layer freeformed by the adjustable nozzle, in which the opening is reduced from 12 mm to 2 mm. The experimental results have indicated that the nozzle design tested is capable of adjusting a layer width. This proves the feasibility of the concept for a

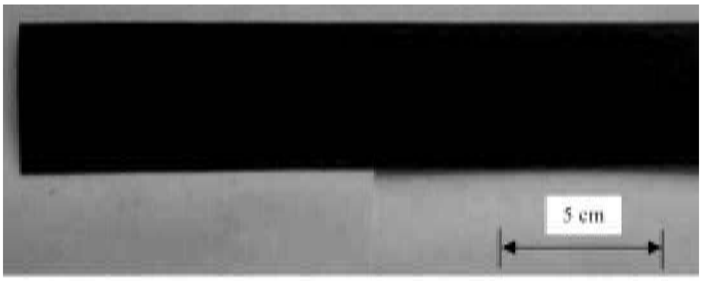
Figure 11 Assembled adjustable planar nozzle



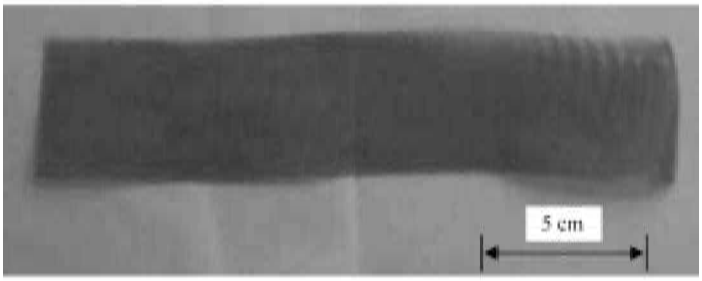
(a) Top view

(b) Bottom view

Figure 12 Layers deposited by adjustable planar nozzle

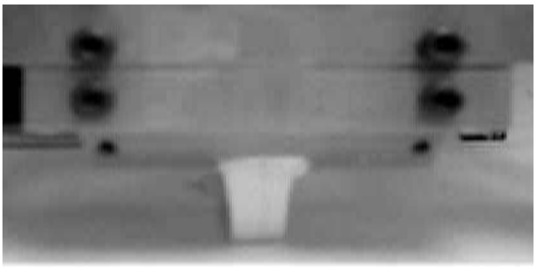


(a) ABS polymer

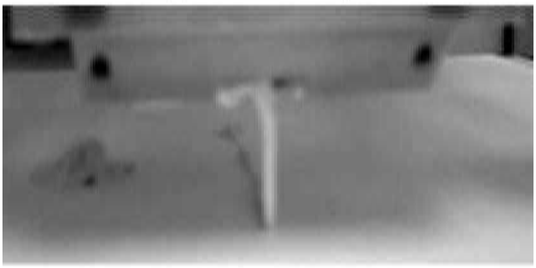


(b) Blue wax

Figure 13 Layers formed by adjustable planar nozzle



(a) 12-mm wide layer



(b) 2-mm wide layer

planar layer deposition (PLD) technique with the materials considered.

Concluding remarks

Two deposition techniques for solid freeform fabrication have been presented in this paper. The first deposition technique studied is one that can deposit variable sizes of filaments in a controlled manner; this technique can build very thick layers with the required tolerance to speed up the whole freeform process. The second technique uses an adjustable planar nozzle to form layers directly; this improves the conventional point-by-point fabrication approach to a layer-to-layer building process and can save a great many deposition passes or scans in building a complete layer. Furthermore, the required slicing software and control system can be greatly simplified because this approach does not need additional algorithms or steps to further break down a layer into lines and points. As a result, these two techniques are much more efficient than would be possible to achieve using the existing freeform fabrication techniques and should have a great potential not only to reduce the machine cost by using the adjustable-nozzle design, but also to increase the machine versatility by fabricating metal and ceramic parts.

Laboratory-scale apparatus has been built to assess the feasibility of these two techniques. Several low-melting temperature materials have been selected for the feasibility study. Experiments are conducted at typical operation conditions. Analytical solutions have also been developed to provide necessary information for designing and refining the apparatus and to study the effects of changing major operational parameters on the formation of filament or layer in the techniques considered. All results indicate that the analytical predictions agree very well with the experimental observation.

It has also been found that since the nozzles in both systems are required to be adjustable or movable in operation, the filaments or layers formed from these materials have a great tendency to be unstable, especially during a rapid adjustment of the effective diameter or the layer width. As a result, the dynamic and thermal effects caused by the rapid adjustment of the nozzle size are not only significant but also complicated. A better understanding of the dynamic and solidification effects on filament and layer forming is critical in the successful implementation of these two freeform fabrication techniques. In the future, these dynamic and thermal effects should be studied. A predictive model to simulate the deposition dynamics and thermal behaviors should be developed. This model can be used to study the relationship between the processing parameters and the shape of formed structures to better control these two freeforming processes. Measurement of dimensional and mechanical properties of the deposition is also important to verify and to further refine the model developed and should be conducted in the future.

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