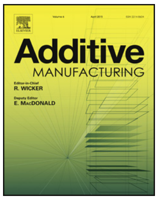
Additive Manufacturing xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Additive Manufacturing

journal homepage: www.elsevier.com/locate/addma



Full length article

Additive manufacturing of 3D structures with non-Newtonian highly viscous fluids: Finite element modeling and experimental validation

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ARTICLE INFO

Article history:
Received 15 February 2016
Received in revised form 10 October 2016
Accepted 27 October 2016
Available online xxx

Keywords:
Nozzle dispensing additive manufacturing
3D printing
Polysiloxane
Silicone
Finite element modeling
Level-set method
Non-Newtonian fluids

ABSTRACT

Additive manufacturing (AM) of highly viscous materials, e.g., polysiloxane (silicone) has gained attention in academia and different industries, specifically the medical and healthcare sectors. Different AM processes including micro-syringe nozzle dispensing systems have demonstrated promising results in the deposition of highly viscous materials. This contact-based 3D printing system has drawbacks such as overfilling of material at locations where there is a change in the direction of the trajectory, thereby reducing the printing quality. Modeling the continuous flow of a highly viscous polysiloxane in the nozzle dispensing AM system using finite element analysis will be the first step to solve this overfilling phenomenon. The results of simulation can be used to predict the required variation in the value of pressure before the nozzle reaches a corner. The level-set method is employed for this simulation, and the results are validated by comparing the flow profile and geometrical parameters of the model with those of the experimental trials of the dispensing of polysiloxane. Comparisons show that the model is able to predict the location of the droplet before it reaches the substrate, as well as the height of the droplet generated on the substrate accurately. To predict the width of the droplet, adjustment factors need to be considered in calculations based on the value of the pressure.

1. Introduction

Material extrusion additive manufacturing (AM) is one of the seven classes of AM, based on the ASTM standard. Nozzle dispensing is one of the techniques used under this class of AM that has gained attention from academia and industry due to its emerging applications in different areas from electronics and microsystems packaging [1] to tissue engineering [2,3]. This technology has been reported to be the most widely used method in bio-manufacturing and life sciences [4,5]. Different researchers have also employed the excellent capability of these systems in fabrication of two- and three-dimensional structures in the electronics industry [6–8]. These flow-based systems are considered a sub-group of material extrusion AM technologies in categorizations suggested by different experts [9–11]. Material extrusion includes a wide range of different AM processes and different definitions have been proposed for it. However, all these definitions include the following characteristics: (1) the ability to produce 3D objects; (2) the ability to manufacture on planar and non-planar surfaces; (3) the ability to feed a wide range of materials including metals, polymers, ceramics, biomaterials, etc.; and (4) the ability to fabricate structures at different dimensional scales [1]. As an AM technology, nozzle dispensing systems also fabricate solid freeform structures by the injection of a continuous stream of fluids onto a surface using a robotically controlled nozzle. Moving the nozzle in vertical direction and depositing a new layer of fluid on top of the previous layers and/or support structures make manufacturing of a 3D object possible [12]. Then, the dispensed fluid turns into solid by cooling, photo-curing, or solvent evaporation [11].

Several advantages of nozzle dispensing technology include having low material waste, reducing the manufacturing time by omitting the tooling steps, and depositing materials on the non-flat surfaces [13]. Compared to other AM methods, nozzle dispensing systems are well-suited for the deposition of fluids with viscosities up to 6×10^7 mPa.s [12,14]. This capability of nozzle-based systems in the deposition of highly viscous materials is extremely important in biomedical and tissue engineering applications as materials used for production of implants, prostheses, and scaffolds are usually non-Newtonian polymers with high molecular weight and consequently high viscosity [4]. Different dispensing mechanisms are used to push the fluids through a nozzle in nozzle dispensing systems, with pressure-actuated (pneumatic) and

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http://dx.doi.org/10.1016/j.addma.2016.10.008
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Please cite this article in press as: F. Liravi, et al., Additive manufacturing of 3D structures with non-Newtonian highly viscous fluids: Finite element modeling and experimental validation, Addit Manuf (2016), http://dx.doi.org/10.1016/j.addma.2016.10.008

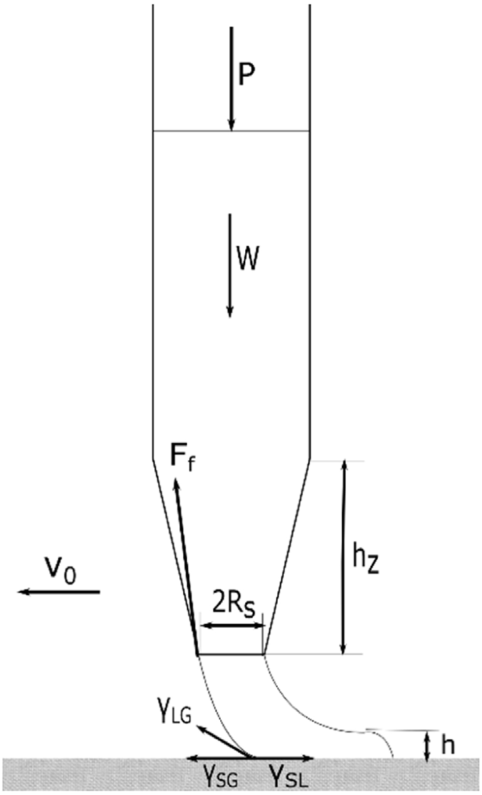

Fig. 1. Influential forces in fluid dispensing [16].

mechanical dispensing systems being the most popular [11]. In pressure-actuated nozzles, time-controlled compressed air is used to activate the deposition process. Simple mechanisms of these nozzles along with their easy operation and maintenance are the reasons for their widespread adoption for in-house developed AM systems. Mechanical dispensing systems use either a screw-based or a positive-displacement mechanism, which generates the required force for deposition by rotation of a stepper motor or linear displacement of a piston, respectively [4]. Although mechanical dispensing systems provide better control for low volume feed rates of fluids, they have a maximum force limit which will constrain their application in dispensing highly viscous materials [4,12]. As a result, among prevalent AM technologies, the pressure-actuated nozzle dispensing system is more suited for fabrication of 3D structures from viscous materials [14]. The feasibility of using this technology for AM of polysiloxane with a viscosity of approximately 40,000 mPa s has been investigated in another study [15].

For the pressure-actuated dispensing system, a combination of proper air pressure, printing velocity, and distance of the nozzle tip from the substrate determines the quality of the final shape. Among material properties, viscosity and surface wetting parameters influence the final shape of printed features and the resolution of 3D printing process [14]. Vozzi et al. introduce the driving pressure produced by compressed air (P), the polymer surface tension (γ), and the friction between the fluid and the internal nozzle wall (F_f) as the main forces determining the flow of viscous materials in nozzle dispensing systems [16]. Fig. 1 depicts the mentioned forces.

In the dynamic fluid model proposed by Vozzi et al., the width of deposited fluid (a) can be calculated from the internal radius of the nozzle (R_s), the viscosity of fluid (μ), the printing velocity (v_0), the height of printed pattern (h), the length of the tapered zone of the nozzle (h_z), and the air pressure (P) using Eq. (1).

$$a = \frac{\pi R_s P}{8\mu v_0 h h_z} \tag{1}$$

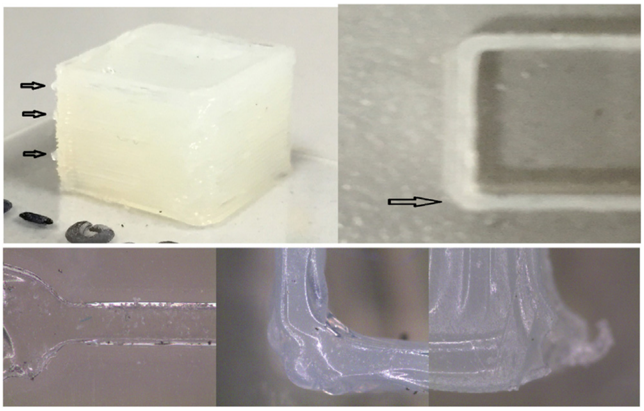

Fig. 2. Overfilling of polysiloxane in nozzle dispensing system.

The model was developed by considering the air driven-pressure as the dominant force that induces deposition. This simplified model can be employed to estimate the dimensions of the printed patterns based on the flow conditions. However, it is assumed that the model is valid for the materials with a viscosity of less than 700 mPa s. A more precise two-tier model has been developed by Vlasea et al. [17]. In this model, the fluid's flow through the nozzle was estimated and then it was related to the dimensional parameters of the injected fluid. However, both of these models have been developed to predict the geometry of Newtonian low viscous materials.

Although the focus of this study is the continuous flow of fluids in material extrusion systems, the printing velocity (v_0) is considered to be zero, so that the dimensions of the droplet can be estimated at the corners where the nozzle's velocity is equal to zero. This assumption also makes the finite element modeling computationally feasible. Hence, by applying the back pressure for a certain amount of time, the process can be treated as a droplet generation and breakup phenomenon for the highly viscous silicone. Zhang et al. have studied the effects of different influential forces on the dynamics of droplet formation for Newtonian fluids [18]. In their work, the increment in viscosity has been introduced as the most important factor in increasing the length of pendant droplet before breakup which will consequently increase the volume and final dimensions of the droplet. More research has been conducted on the behavior of the droplets of Newtonian and low viscous fluids in dripping [19,20] and drop-on-demand jetting [21,22]. In a review of the applications of droplet formation by Basaran, the importance of studying the generation and the breakup of complex non-Newtonian fluids has been emphasized [23]. The effect of viscoelastic properties on the drop formation for the low viscosity polymers was studied by Tirtaatmadja [24]. The results of their work showed that the viscoelastic properties are irrelevant to the drop formation phase, however, they will result in creation of a long cylindrical filament that delays the separation of the droplet from the nozzle. Yıldırım et al. studied the dynamics of droplet formation for both shear-thinning and shear-thickening non-Newtonian fluids for the first time [25]. Based on their work, using a shear-thinning fluid such as polysiloxane can prevent the formation of satellite drops while jetting. It also reduces the length of cylindrical filament created because of the viscoelastic properties of the polymer.

The optimization studies carried out in^{15} guarantee the uniform dispensing of hairpin patterns of polysiloxane. The main drawback of this method is the agglomeration of polysiloxane where there is a change in the direction of the nozzle movement, e.g., in the corners. Fig. 2 illustrates this overfilling phenomenon, also called swelling. This issue arises from the fact that the value of the pressure is

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