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What makes a material printable? A viscoelastic model for extrusion-based 3D printing of polymers

Chad Duty[a,b,*], Christine Ajinjeru[a], Vidya Kishore[a], Brett Compton[a], Nadim Hmeidat[a], Xun Chen[b], Peng Liu[b], Ahmed Arabi Hassen[b], John Lindahl[b], Vlastimil Kunc[a,b,c]

[a] University of Tennessee, United States
[b] Manufacturing Demonstration Facility, Oak Ridge National Laboratory, United States
[c] Purdue University, United States

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ABSTRACT

This article presents a practical model for evaluating polymer feedstock materials as candidates for 3D printing across a variety of extrusion-based platforms. In order for a material to be successfully utilized for 3D printing operations, a series of fundamental conditions must be met. First, pressure-driven extrusion must occur through a given diameter nozzle at a specified flow rate. Second, the extruded material must form and sustain the desired shape. Third, the extruded structure must be able to bridge a specified gap and serve as a mechanically sound foundation for successive deposits. Finally, the deposited structure must be dimensionally stable during the transition to the final state (i.e. fully cured at room temperature). This article presents a framework for extrusion-based printing and a simple viscoelastic model for each of these conditions based on the rheological and thermo-physical properties of the candidate material and the processing parameters of the extrusion-based deposition platform. The model is demonstrated to be a useful tool for the evaluation of example test cases including: high temperature thermoplastics (polyphenylsulfone), fiber reinforced thermoplastics (acrylonitrile butadiene styrene), low-viscosity thermosets (epoxy resins), and thermoplastics with a high coefficient of thermal expansion (polypropylene).

1. Introduction

There are various forms of 3D printing systems that rely on the extrusion of polymer materials. ASTM International generally classifies this approach as "Material Extrusion", defined by material being selectively dispensed through a nozzle or orifice [1]. The most common Material Extrusion platform is Fused Deposition Modeling (FDM™) developed by Stratasys in the late 1980′s. FDM™ thermoplastic materials are supplied as a 1.7 mm diameter filament, which is melted in the deposition head by a resistively-heated cylinder. The filament feedstock is gradually advanced into the melt chamber to extrude a molten bead of material through the heated nozzle, which then moves horizontally to deposit a specific 2D pattern for a given layer. Slight variations on the FDM™ technology have more recently led to the widespread adoption of the desktop 3D printer, generically referred to as Fused Filament Fabrication (FFF). The FDM™/FFF markets offer a wide array of thermoplastic material feedstocks in filament form, the most common of which are acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), polycarbonate (PC), and polyetherimide (PEI).

More recently, large–scale polymer extrusion-based systems [2,3] have been developed that utilize a single–screw extruder rather than a resistively heated cylinder to achieve much higher deposition rates with a pelletized feedstock. For example, the Big Area Additive Manufacturing (BAAM) system under development at Oak Ridge National Laboratory deposits high temperature thermoplastics and composite materials at a rates up to 50 kg/h through a 7.6 mm nozzle inside a build volume of 6 m × 2.4 m × 1.8 m [4,5]. BAAM deposits a variety of neat and fiber reinforced materials across a wide range of deposition temperatures (up to 500 °C). Reinforced materials provide additional strength and stiffness [6,7], but the reinforcing fibers alter the rheological and thermo-physical properties of the material, thus requiring additional process development to determine appropriate deposition parameters [8–13].

Direct Write (DW) is another extrusion-based technology that is commonly used for 3D printing of polymers. This approach deposits tailored viscoelastic feedstocks using syringe-like cartridges that are controlled by either pneumatic pressure or a mechanical plunger. DW is typically used for printing of functional inks, colloidal suspensions, and

* Corresponding author at: 1512 Middle Drive, Knoxville, TN, 37996-2210, United States.
E-mail address: cduty@utk.edu (C. Duty).

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biological inks, but has recently been expanded to print structural thermoset composite materials [14–16]. The DW platform was initially commercialized under the name “Robocasting” [17] for ceramic suspensions, but has garnered wide acceptance for deposition of compliant and reactive compounds, such as silicones and epoxies [18–21]. The typical build volumes for DW platforms are relatively small (~10 cm cube), but a small diameter (~200 μm) extrusion orifice and open platform allows for the deposition of high resolution structures and unique deposition motifs [22–25].

As the application space grows for polymer extrusion-based deposition techniques, several research entities are pursuing the development of specialized and high-performance material systems. These base resin materials can be costly, and with deposition rates exceeding 50 kg/h for certain systems, the prospect of trial-and-error based process development is not feasible. Discrete modeling efforts have been pursued for the liquefier dynamics and associated pressure drop in an FDM process [26–28], the conditions for a successful bond between adjacent deposited beads [29–31], and the thermal history of both FDM and BAAM systems [32–34]. Some commercial codes are available to guide selection among given print parameters [35], however, a unified model has not yet been proposed for the successful extrusion of polymers for 3D printing. Herein, a simple viscoelastic model is presented that addresses each step of the deposition process, from pressure-driven flow to distortion of the final part, and evaluates the ability of a given material to meet the criteria for successful 3D printing. This basic model is based on processing parameters for the deposition platform of interest and the thermo-physical and rheological properties of the candidate material [36].

2. Deposition systems and material properties

As described above, there are three primary extrusion-based deposition platforms of interest to this study: Fused Filament Fabrication (FFF), Big Area Additive Manufacturing (BAAM), and Direct Write (DW). The common printing parameters for each of these platforms are described below as well as definitions for the appropriate nomenclature. Each of the platforms use the same basic extrusion geometry shown in Fig. 1. The independent variables for an extrusion-based process are defined below and typical values for each deposition platform are listed in Table 1.

Q = volumetric flow rate of extruded material
P_{max} = maximum system pressure
t_{layer} = time to deposit a single layer
D_E = diameter at the exit of the extrusion head
L_E = length of the extruder exit region
D_n = diameter of the nozzle leading up to the extruder exit
L_n = length of the nozzle leading up to the extruder exit
T_{amb} = ambient temperature of the build chamber
T_{dep} = deposition temperature
T_{sub} = substrate temperature of successive deposited beads
h = deposited bead height
w = deposited bead width
H = height of the overall structure
L = length of the overall structure

In order to simplify the extrusion-based deposition process in a conservative manner, this model assumes that the initially deposited layer remains at the deposition temperature (T_{dep}) during the entire first layer (t_{layer}) and the temperature of the remaining structure (T_{sub}) maintains the chamber temperature ($T_{sub} = T_{amb}$). For thermoplastic materials, T_{amb} is generally considered to be equal to the glass transition temperature (T_g) or room temperature (RT). For thermoset materials typically used for DW, all three temperatures (T_{dep}, T_{sub}, T_{amb}) are assumed to be at room temperature. The layer time (t_{layer}) and overall structure height (H) are relatively arbitrary, but are respectively considered to be 60 s and 20 times the bead height for this model.

The basic rheological and thermo-physical properties needed to

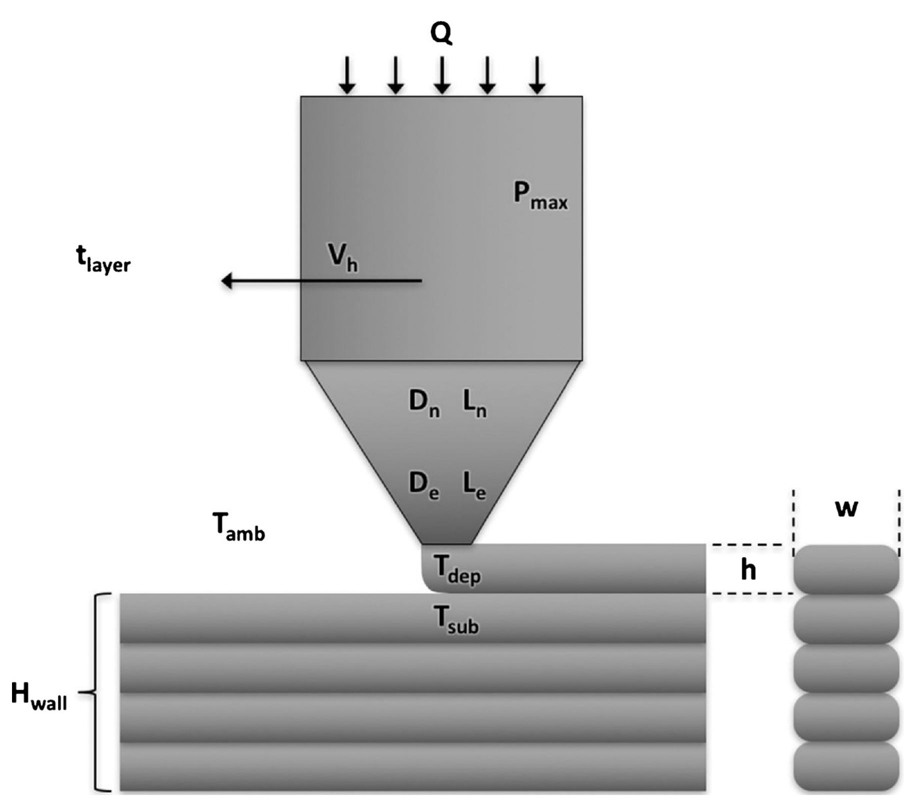

Fig. 1. Deposition parameters for typical extrusion-based deposition platforms.