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Model analysis of feedstock behavior in fused filament fabrication: Enabling rapid materials screening

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ABSTRACT

This research presents a rapid screening process for analyzing the extrudability of polymeric materials for filament extrusion based additive manufacturing (AM) by predicting extrusion failure. This rapid screening process can further suggest optimal Fused Filament Fabrication (FFF) processing conditions for a specific material. Annular backflow and filament buckling, which are the two primary failure modes during extrusion in FFF, are considered in this study. The screening method focuses on model analysis of annular backflow while simultaneously considering a previously developed model for filament buckling and includes the introduction of a non-dimensional number (Flow Identification Number, or FIN) that predicts a material's propensity to backflow based on a rheological analysis and the system geometry. Annular backflow was modeled by calculating velocity profiles and determining the normalized net flow magnitude. The backflow and buckling models were experimentally verified with acrylonitrile butadiene styrene, low density polyethylene, and sodium sulfonated poly(ethylene) glycol. We empirically validated that the FIN was able to accurately predict backflow and that the potential to backflow and, by extension, propensity to fail during extrusion, is most sensitive to fluctuations in filament diameter and the material's shear thinning behavior. Our results demonstrate the importance of printing in the shear thinning regime to reduce the effect of processing conditions on the extrudability of a polymer.

1. Introduction

Additive manufacturing (AM, also referred to as “3D Printing”) has the potential to revolutionize the manufacturing process for a broad range of products [1]. The layerwise approach of AM processes affords the opportunity to create complex geometries that are not possible with traditional manufacturing processes and to produce complete parts and consolidated assemblies with very little waste. While examples of the use of AM to fabricate end-use products are expanding, widespread industrial adoption of the technologies is limited due to limitations of process repeatability, final part properties, and material selection [2].

These limitations are especially prevalent in Fused Filament Fabrication (FFF), also trademarked as “fused deposition modeling”, the most prominent type of AM process [3]. A type of the Material Extrusion AM modality [4,5], FFF features the selective deposition of a softened thermoplastic through a nozzle. Specifically, a polymer filament feedstock is fed via counter-rotating rollers into a nozzle where it is heated to a temperature at which it is fluidic. The solid filament above the fluidic zone acts as a piston to extrude the molten polymer out of the nozzle. This process is analogous to the operation of a capillary rheometer, where a metal piston applies force to expel a heated polymer melt through a convergent capillary die. Material extrusion AM is unique in that the filament acts as

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both piston and extrudate. The FFF system's motion gantry enables precise deposition of single “roads” of the polymer extrudate to create each layer of a part [6–8].

There is extensive current research focus on expanding the capabilities of this process to enable the production of end-use parts. A key need is efficient discovery of a more diverse catalog of available materials to be used in the extrusion AM process [1]. The most widely implemented materials in consumer desktop systems currently include polylactic acid (PLA) and poly(acrylonitrile-co-butadiene-co-styrene) (ABS). Poly (ether imide), polycarbonate, polyamide, and other primarily amorphous thermoplastic polymers are also used in a smaller capacity and with restrictions based on machine requirement or physical properties that make complex part geometries difficult, such as crystallization and thermal expansion induced shrinkage and part warping [9–12]. This limited palette serves as the motivation to produce new materials for FFF with a broader range of thermal and mechanical properties for additional markets and applications. A key challenge hindering this desired discovery is that there is no formalized process for designing, screening, and evaluating materials for FFF. Current approaches tend not to focus on materials-level screening, and are instead focused primarily on the use of design of experiments approaches to identify process parameters, which is both expensive and time consuming [13].

Development of new materials for the FFF process requires screening across all areas of the printing procedure: (i) filament creation from feedstock, (ii) filament feeding and liquefaction in the nozzle, (iii) liquefied filament extrusion, and (iv) road solidification and geometry formation. The goal of this paper is to provide a model to enable screening of new materials for failure during the filament feeding and liquefaction processes. The three primary failure modes that would prevent a material from being used in FFF, shown in Fig. 1, include inconsistent filament diameter, annular backflow, and filament buckling [8].

Improper filament diameter failure can be eliminated by refining the filament fabrication methods with tight diametric tolerances. This failure mechanism will not be discussed further. Filament buckling has been explored by Venkataraman et al. [6]. In their work, the authors suggest that a filament will buckle if the pressure applied by the rollers exceeds that of the material's critical buckling stress. The authors estimated this relationship by calculating the ratio of the elastic modulus to the apparent viscosity measured using a capillary rheometer. They discovered that as long as the ratio is greater than a critical value, the material will extrude in FFF for a specific geometry and flow rate. Their work addresses the general buckling failure mode but does not account for the relationship between system geometry and flow behavior of the polymer at the solid-liquid interface, which is necessary for a complete screening analysis.

Annular backflow, shown in Fig. 2, which accurately depicts the geometry of an E3D-V6 hot end nozzle as described in schematic diagrams provided by, and used with permission from, E3D (see supplementary information), is only possible because the filament that acts as a piston to extrude the molten material is not perfectly flush with the liquefier wall. In this failure mode, the molten polymer can flow back up the annular region between the filament and the liquefier wall, escape the heated area, and cool below its solid/fluid transition temperature. Little work has been done to model annular backflow, or to generally characterize the fluid behavior during the liquefaction process in FFF. Understanding this phenomenon is vitally important during the screening process of AM filament material development. For instance, polymeric materials that have low activation energy for flow can experience multiple orders of magnitude drop in viscosity over a narrow temperature range, e.g. in the solid to fluidic transition in the extrusion nozzle. The solid to liquid transition is vitally important to the extrudability of a material and is assumed to be instantaneous, but the behavior of the material at this interface determines the extrudability of the material. A material that has a high modulus but transitions to a very low viscosity fluid upon heating can experience backflow. This is a potential characteristic that can be found in ionomers of highly inviscid polymers [14].

Developing a rapid screening tool to predict failure modes would be a tremendous asset for systematically generating novel materials for FFF. A screening process would remove the current laborious and time consuming trial-and-error methodologies and support efforts to understand the extrudability of materials in regards to their behavior after extrusion such as those by Tekinalp et al. [15]. This research takes a continuum-based approach to model the rheological behavior of polymer melts in FFF and presents an efficient dimensionless analysis that predicts filament extrudability based on a rheological measurement and the system geometry. Additionally, this work highlights the critical importance

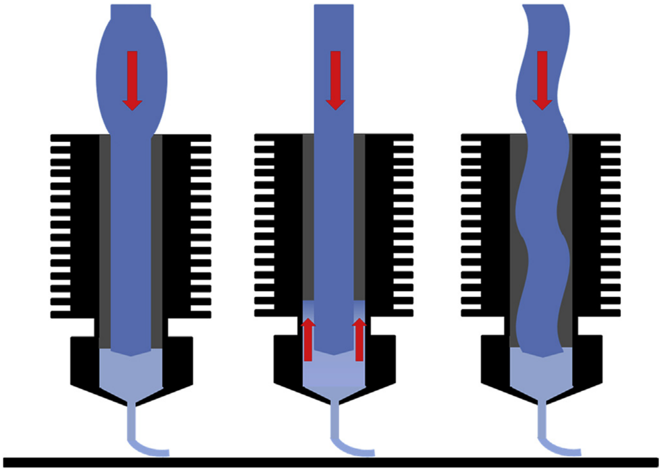

Fig. 1. Material extrusion failure modes, from left to right: inconsistent filament diameter that exceeds the nozzle diameter, annular backflow, filament buckling.

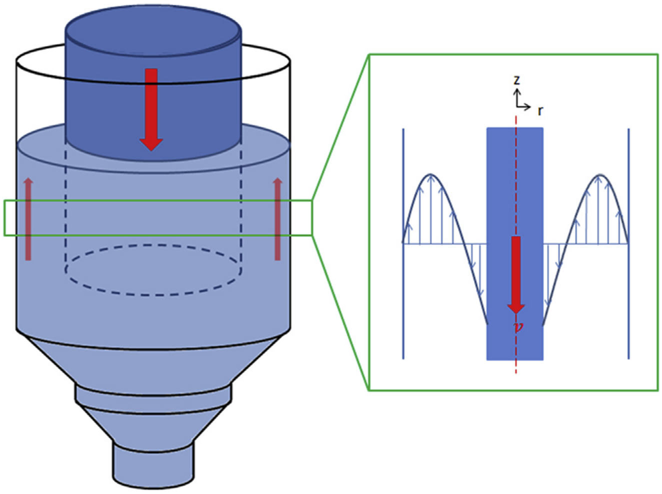

Fig. 2. Schematic of transition of solid filament to viscous fluid in FFF nozzle. Inset image illustrates representative velocity profile in the annulus between the solid filament and nozzle wall, as would be observed during annular backflow. Note the chosen coordinate system and direction. Geometry of nozzle is based on schematic diagram provided by E3D.

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