Fused Filament Fabrication Process

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Three-dimensional printing (3DP), also known as additive manufacturing (AM), has rapidly evolved over the past few decades. Researchers around the globe have been putting their efforts into AM processes improvement and materials development. One of the most widely used extrusion-based technology under AM processes is Fused Deposition Modeling (FDM), also known as Fused Filament Fabrication (FFF). Numerical simulation tools are being employed to predict the FFF process complexities and material behavior. These tools allow exploring candidate materials for their potential use in the FFF process and process improvements. The prime objective of this study is to provide a comprehensive review of state-of-the-art scientific achievements in numerical simulations of the FFF process for polymers and their composites.

Fused Filament Fabrication simulation

1. Introduction

Three-dimensional printing, also known as additive manufacturing (AM), has rapidly evolved over the past few decades [1][2]. AM processes allow the fabrication of three-dimensional and functional components through successive additions of 2D layers [3]. AM was first introduced by Hull [3], since then, researchers have established several process technologies and novel materials [4]. These processes have attracted the research interest due to higher flexibility in the design and the manufacturing of highly customizable parts, rapid prototyping of conceptual products, waste reduction, lower risk of human error, and higher precision and accuracy than conventional manufacturing processes [5][6][7]. AM processes are now being widely adopted in several industrial sectors owing to these advantages [8][9].

Fused Deposition Modeling (FDM), also known as Fused Filament Fabrication (FFF), one of the most widely used AM processes, was proposed and developed by Scott Crump at Stratasys [10]. In the FFF process, the material is supplied to the 3D printer in the form of filaments. The extruder in any FFF-based 3D printer generally contains a feed material control mechanism, heating chamber, and nozzle. The material in the filaments form is fed to the control system, which controls the feed rate. Then the filament moves through the heating chamber, which converts it into a semi-solid phase and then passes through the nozzle for deposition on the printing bed [11]. The mechanical and thermal controls in the extruder govern the overall printing process and depend upon the feed-stock material properties. Thermoplastics, particles reinforced polymers, and hydrogels have been fabricated using the FFF process [12].

Researchers around the globe have been putting their efforts into AM processes improvement and novel materials over the past few decades [13][14]. The research efforts include process printing speed, printer build volume, and production rate [15]. The materials portfolio has also included short and continuous fiber-reinforced polymer composites for the FFF process [16][17][18]. Aside from the extensive experimental investigations on the FFF process reported in the literature, the numerical tools employed are still limited.

2. Physics Involved in Fused Filament Fabrication Process

This section presents the physical phenomena involved in the FFF process. An in-depth understanding of this phenomenon is essential to improve the process and 3D printed part quality. The overall FFF process can be divided into three phases; material flow through the nozzle and deposition on the print bed or already deposited material (extrusion), interaction of deposited beads to make a bond (fusion), and the cooling process (solidification), as elaborated in **Figure 1**.

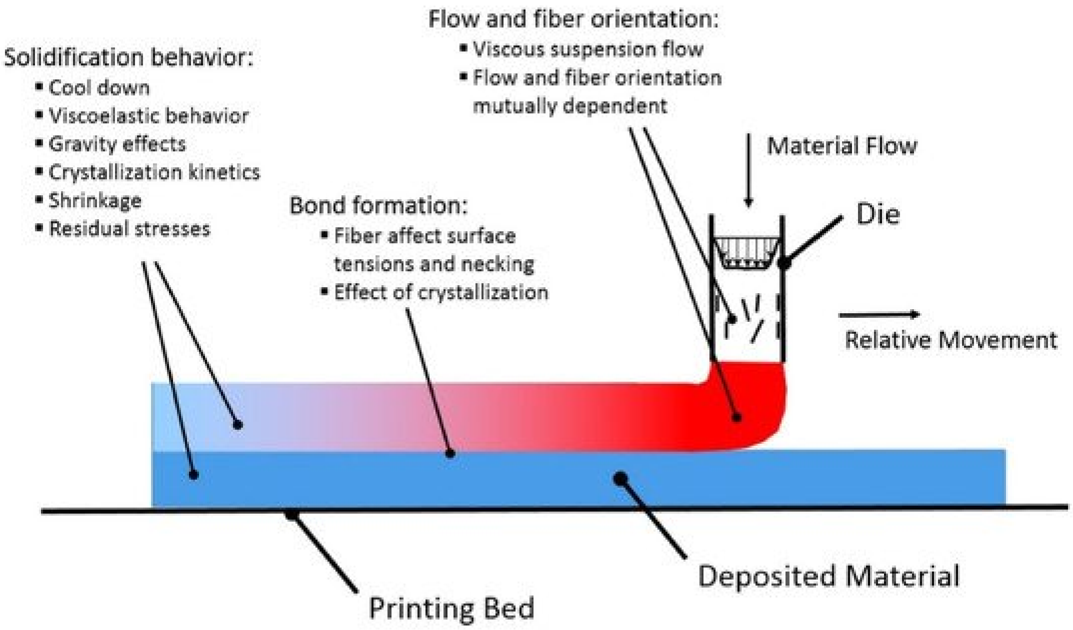

Figure 1. Schematic diagram of the FFF process. Reprinted with permission from reference [19]. Copyright 2018, Elsevier.

The first process involves material flow through the nozzle body, nozzle orifice, and deposition [20]. This phase is of great interest, especially in the 3DP of fiber-reinforced polymer composites, as fiber orientation results from material flow through the orifice and regulates mechanical behavior (anisotropy) of the fabricated part. The flow behavior and fiber orientation are interdependent, as a viscous fiber-suspension flow is obtained for materials with considerable fiber volume fractions. Shear alignment phenomena and converging zone in nozzle determine the fiber orientation in printed beads. The viscosity of the material is also dependent upon fiber orientation. For example, the extensional viscosity parallel to fiber alignment is multiple folds higher than in the transverse direction.

In the second phase, the deposited material reheats or re-melts the already deposited material beads [21]. The bonding between the extruded filaments is highly dependent on this wetting phenomenon [22]. The wetting phenomena regulate the contact area between the deposited filaments, as prolonged interface exposure at elevated temperatures assists the merging of adjacent beads and polymer chains diffusion [23]. The viscosity of beads in the transverse direction and surface tension of the material controls this wetting process. A limited temperature range is available for perfect bead formation between the layers, as viscosity is temperature-dependent [24]. Diffusion-based fusion is observed between the beads at higher temperatures after an interface has been formed. However, the diffusion process is obstructed due to reduced molecular mobility at lower temperatures. Therefore, a critical factor for adequate bonding is the temperature history of printed material. Additional complexity arises for semi-crystalline materials, as the viscosity of such materials rapidly increases at crystallization temperature, interrupting the bond formation process [25].

Lastly, the deposited material begins to solidify as it cools down. The cooling process during and post-printing is governed by convective and radiative heat losses on external surfaces of the beads and conductive heat transfer at beads contact points and printing bed. If the material is deposited at a higher speed, i.e., a large amount of material is deposited in a shorter time, it will not allow the pre-laid layer to cool down sufficiently before depositing the next layer [26]. It will result in sagging due to gravity and print failure. The material converts to a viscoelastic solid from a viscous fluid during the cooling process and starts shrinking depending upon the coefficient of thermal expansion (CTE). The internal stresses begin to develop due to material stiffness produced by the solidification process and restriction due to bead fusion. Viscoelastic relaxation and material deformations assist a fraction of internal stresses to be released. However, for semi-crystalline polymers, the mechanical and thermal properties change during the crystallization process. For such materials, additional strains are observed that further cause internal stresses and part deformations, resulting in altered mechanical properties [27]. The presence of fibers aligned in the printing direction also affects the thermal properties due to increased thermal conductivity. Thermomechanical and crystallization effects constraints the shrinkage process in the bead direction, but not to the same degree in the lateral direction [28]. The physical phenomena involved in the FFF process highlight its complexity. Therefore, the above-discussed process physics and interactions must be considered for more realistic process simulation and modeling.

3. Future Outlook

The fused filament fabrication process has been under continuous development since the commercial availability of this technology. Several studies reported experimental analysis and virtual modeling of different phases involved in the process. The numerical modeling of material flow inside/outside the printing head and behavior after deposition with promising outcomes have been reported. Based on the extensive literature review performed on numerical simulation techniques, the following research challenges and gaps are identified:

- **Fiber Orientation:** The fiber orientation in deposited beads depends upon the material flow through the nozzle and deposition process. Most of the literature reports the use of Newtonian isotropic fluid properties; however, these materials should be modeled under anisotropic viscous flow conditions. Current modeling software cannot solve fourth or higher-order orientation tensors and cannot consider anisotropic flow characteristics (which is the case with fiber-reinforced composites). Therefore, there is a need for better numerical simulation tools to consider realistic fiber orientation during material flow.

- **Beads Deposition:** Several heat transfer models have been reported in the literature to predict the cooling process of the deposited beads. However, due to the anisotropy involved in the 3DP process, interlayer conduction phenomena need to be considered as thermal conductivities of deposited beads change with the fiber orientation.

- **Interface and Bonding:** Bonding between the subsequent layers is highly correlated with the interface; therefore, the presence of fibers on the bead surface can affect this process. In addition, the necking phenomenon is derived by the gradients of surface tension is also influenced by the bead surface morphology. Finally, the material behavior (crystalline or amorphous) will reflect its viscosity, which ultimately affects the bonding process; therefore, it must be accounted for accurate process modeling.

- **Integrated Simulation Models:** The FFF process is a complex multi-stage process as described in this paper. However, most reported computational work either focused on the material flow inside the liquefier or material behavior after deposition and is not as mature as the experimental literature. Therefore, there is a need for integrated studies considering all these phases of the FFF process (i.e., melt flow behavior inside/outside the nozzle, material deposition, solidification behavior, bond formation, and warpage and residual stresses).

- **Model Validation:** The validation of numerical and analytical models is vital through experimental studies. Limited studies compared the numerical simulation results with experimental work, which is essential for validating and broader application of these models.

- **Materials Portfolio:** Materials portfolio for the FFF process is rapidly growing. However, few materials (such as PLA and ABS) are considered for numerical and analytical modeling of process or material behavior. The researchers should focus on implementing existing models to a broader range of materials or develop models for materials not yet considered in the literature.

- **Polymer Composites:** Two-phase materials (composites) are also barely considered for the numerical modeling of material or the FFF process. The most reported models address linear amorphous polymers. Different polymers exhibit different characteristics, such as bare PLA and ABS act as amorphous materials; however, PBT, PA12, and PEEK exhibit a semi-crystalline nature [29][30][31]. Moreover, the addition of the reinforcing phase can alter the nature of the resulting composite material, e.g., PLA acts as semi-crystalline material with tricalcium phosphate (TCP) [32]. The effect of reinforcement type and process parameters on polymer nature (amorphous or crystalline) will be worth addressing.

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