Experimental and numerical investigation of extrudate swell of polylactic acid (pla) via material extrusion (mex) additive manufacturing process

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Abstract

Extrudate swell is a rheological phenomenon of polymers taking place after emerging the extrusion die due to the residual molecular stress relaxation, which is of great essential for ensuring the precision and stability of products manufactured by Material Extrusion (MEX) Additive Manufacturing (AM) process. Extrudate swell can be affected by multiple factors including the material properties and processing parameters that can be coupled and make it challenging to fully understand their effects, especially in absence of precise online measurement techniques. In this study, we investigated experimentally the extrudate swell as a function of the extrusion rate, melt temperature and nozzle diameter for polylactic acid (PLA). The Computational Fluid Dynamic (CFD) and Level Set (LS) method in COMSOL Multiphysics were used to simulate the polymer flow exiting the extrusion nozzle exit. The simulation results match well with experimental results and show that the swell ratio decreases with increasing temperature and nozzle diameter and decreasing extrusion rate. These results can be used to optimize the parameters of EAM processes.

1. Introduction

Material Extrusion (MEX) Additive Manufacturing (AM) process [1], among the most widely used AM processes, involves extruding materials in their molten state through a die/nozzle and depositing them layer by layer to build complex shapes. The materials can be thermoplastics polymers or feedstocks composed of a binder and metal or ceramic powders, in filament or pellet shape. However, the viscoelasticity of the polymer melt would result in swelling of the extrudate, which can reduce the dimensional accuracy of the part or even lower the mechanical strength due to poor adhesion among the extrudates [2]. The extrudate swell can be affected by multiple factors, such as imposed shear stress, temperature, molecular weight and channel geometry [3]. Thus, understanding and tailoring the effect of the processing parameters on the extrudate swell is an important aspect in improving the quality of MEXAM manufactured parts.

This study presents the experimental measurements of the extrudate swell of polylactic acid (PLA) regarding melt temperature, extrusion rate and nozzle diameter. The numerical simulation

was realized using COMSOL Multiphysics software. These results and analyses allow to predict and optimize the extrudate swell in MEXAM process.

2. Material and methodology

A dynamic camera was used to capture the images of the extrudate swell and an infrared was used to measure the temperature of the extrudate. Both cameras were installed perpendicular to the extrudate flow direction. Two nozzles with same extrusion length L and different nozzle diameter D were tested. The temperatures of 190°C, 200°C and 210°C were tested, and each temperature was related to four extrusion speed (Rotation speed of the screw at 10, 20, 30 and 40 rpm).

The shear viscosity is determined at low shear rate with a rotational rheometer and at high shear rate with a capillary rheometer. The shear viscosity (1) dependents on shear rate and temperature, and the dependencies are modelled by Carreau- Yasuda model (2) and Arrhenius model (3) respectively:

$$\eta(\dot{\gamma}, T) = a_T \eta(\dot{\gamma}, T_0) \tag{1}$$

$$\eta = \eta_\infty + (\eta_0 - \eta_\infty)(1 + (\lambda\dot{\gamma})^a)^{\frac{n-1}{a}} \tag{2}$$

$$a_T = \exp\left[\frac{E_a}{R}\left(\frac{1}{T} - \frac{1}{T_0}\right)\right] \tag{3}$$

where η_0 is the viscosity for zero shear rate, η_∞ the viscosity at infinite shear rate, λ the characteristic time of the material, a the parameter adjusting the transition regime between the Newtonian plateau and the shear-thinning regime, n the pseudo- plasticity index, γ the shear rate, T the temperature, T_0 the reference temperature, E_a the activation energy and R the gas constant.

The numerical simulation was carried out by using Computational Fluid Dynamics (CFD) in COMSOL Multiphysics software. In addition to the built-in Navier-Stokes equations which describes the motion of the fluid, the Level Set (LS) method (4) was used to track the interface of two immiscible fluids (polymer and air in this case).

$$\frac{\partial\phi}{\partial t} + \nabla(\boldsymbol{u}\phi) = \gamma\nabla\left(\varepsilon_{ls}\nabla\phi - \phi(1-\phi)\frac{\nabla\phi}{|\nabla\phi|}\right) \tag{3}$$

where ϕ is the volume fraction of the polymer in the computational volume, t the time, $\boldsymbol{u}$ the velocity vector, γ the reset parameter and ε_{ls} the interface thickness control. The volume fraction varies between 0 and 1, with 1 indicating a complete filling of the designed volume by the polymer. The value 0.5 is assigned to the interface between the polymer and the air.

Figure 1 represents the geometry of the model and the boundary conditions for the simulation of flow existing the nozzle.

T_m and T_{env} represent the melt temperature and the environment temperature respectively.

3. Results and discussion

Figure 2 compares the swell ratio (ratio of extrudate diameter to nozzle diameter) between experimental and numerical results. Figure 2 (a) shows that for the extrusion of PLA at 200°C, the swell ratio increases with increasing the extrusion rate for both nozzles while the nozzle of larger diameter has lower swell ratio, which is in accordance with literature [4]. Figure 2(b) shows that the

swell ratio decreases with increasing the temperature. The deviation between the simulation results and experimental results was within 4%, which proves that the simulation correlates well with the experimental results and can be used to investigate and optimize the processing parameters. According to the above results, it can be concluded that reducing the extrusion swell can be achieved by decreasing the extrusion rate, increasing the melt temperature and nozzle diameter, but the printing speed and dimensional resolution should be considered.
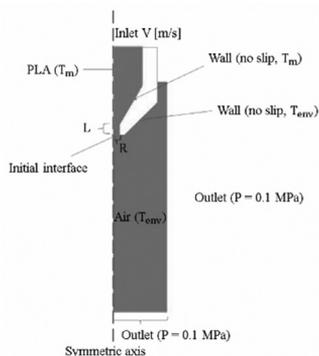

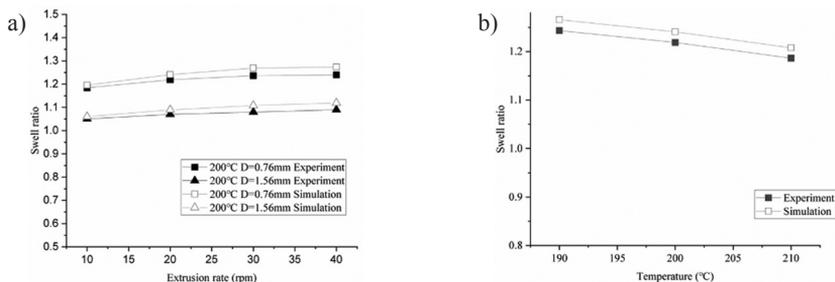**Figure 1.** Geometry of the model and related boundary conditions for the swelling simulation.

Figure 2. Comparison of experimental and numerical results of swell ratio
for (a) extrusion rate and (b) temperature (20 rpm).

References

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