DTU Library

Numerical Study of the Impact of Shear Thinning Behaviour on the Strand Deposition Flow in the Extrusion-Based Additive Manufacturing

Serdeczny, Marcin P.; Comminal, Raphaël; Pedersen, David B.; Spangenberg, Jon

Published in:
Proceedings of the 18th International Conference of the European Society for Precision Engineering and Nanotechnology

Publication date:
2018

Document Version
Publisher's PDF, also known as Version of record

Numerical Study of the Impact of Shear Thinning Behaviour on the Strand Deposition Flow in the Extrusion-Based Additive Manufacturing

Marcin P. Serdeczny[1], Raphaël Comminal[1], David B. Pedersen[1], Jon Spangenberg[1]

[1] Department of Mechanical Engineering, Technical University of Denmark, Kgs. Lyngby, Denmark

mpse@mek.dtu.dk

Abstract
This paper investigates the influence of shear-rate dependent viscosity on the strand deposition flow during Extrusion-Based Additive Manufacturing. Extrusion-Based Additive Manufacturing, also known as Fused Deposition Modeling (FDM), is a manufacturing method in which material is joined layer by layer into a 3D object. A solid filament is heated above the melting point and extruded through a nozzle to form a strand. The process is modelled within the paradigm of Computational Fluid Dynamics as an isothermal Generalized Newtonian fluid flow. The power law is used as the constitutive relation between the shear-rate and the viscosity. A sensitivity study of the model's input parameters (power-law index and consistency index) is made. The simulations are performed varying two process parameters: the vertical distance between the substrate and nozzle exit as well as the relative horizontal velocity between the substrate and nozzle. The model is used to investigate the cross-sectional shape of the strand after the deposition and the force exerted on the substrate by the material extruded from the nozzle (the printing force). Under the tested conditions, we find a neglible change in the cross-sectional shape and the printing force behaviour when varying the power-law index and the consistency index. Thus, it is concluded that the Newtonian fluid model provides a sufficient approximation to simulate the deposition flow under the given assumptions.

3D printing, Simulation, Deposition, Flow

1. Introduction

In Extrusion-based 3D printing, also known as Fused Deposition Modeling (FDM), a thermoplastic material is joined together in a layer by layer manner to form a 3D object [1]. The raw specimen is in form of a solid filament that is fed by rollers to the liquefier where it is heated above the melting point and extruded through a nozzle. The first layer is usually deposited on the support platform while the next layers link to the previously extruded by the means of temperature driven diffusion [2].

FDM offers fewer constraints in geometry design as compared to e.g. injection moulding. However, the process is slow and there is a limited control over the part properties such as the strength, the porosity, and the surface roughness.

One of the steps towards improvement of the FDM method is understanding of the molten plastic flow through the nozzle and its deposition on the substrate. First, the pressure drop in the nozzle determines the force needed to be applied by the rollers to feed the filament [3]. Second, the deposition flow governs the strand shape which is important to model the inter-layer bonding [2, 4] and the cooling of the part [5]. Further, the cross-sectional shape is related to the surface roughness of the part [6] and its porosity [7].

Recently, a numerical procedure to predict the shape of the strand cross-section and the force applied by the fluid on the substrate (the printing force) was presented by Comminal et al. [8]. Under the assumptions of an isothermal Newtonian fluid and a creeping flow, it was found that the filament cross-section can vary significantly, depending on the printing conditions, and that the printing force is linearly dependent on the substrate velocity.

In this work, we go a step further and quantify the impact of pseudoplastic properties of the fluid on the deposition flow in the FDM process. In Section 2, an overview of the physical and numerical model is given together with a summary of the parameters that were used in this study. In Section 3, results of the simulated strand cross-sections and the printing force are shown. We conclude and summarize the study in Section 4.

2. Model and materials

2.1. Description of the physical and numerical model

The model used in this paper is based on work of Comminal et al. [8] and focuses on the flow of the molten filament in the region between the nozzle and the substrate. The geometry of the model is presented in Figure 1. The nozzle is included as a stationary tube with an internal diameter D. The strand is deposited on a planar substrate that moves with a velocity V and is placed perpendicular to the nozzle's axis at a distance g. As the velocities are constant, the two opposite configurations where the nozzle moves and the substrate is fixed, and vice versa, are equivalent. The problem has a symmetry plane so only half of the domain is simulated. The flow is assumed incompressible and isothermal. Although, the temperature variation is limited in the simulated region, the isothermal assumption provides a first approximation of the deposition flow. Finally, a no slip boundary condition between the fluid and the solid walls (the nozzle and the substrate) is assumed.

2.2. Model input and parameters

The materials used in the FDM process are known for their shear thinning properties [9]. The power law is used to represent the shear-rate dependent viscosity of the fluid

$$\eta(\dot{\gamma}) = K\dot{\gamma}^{n-1} \quad (1)$$

where $\dot{\gamma}$ is the shear rate [1/s], K is the consistency index [$Pa \cdot s^n$], and n is the power law index [-]. The material enters the nozzle at the inlet boundary with a uniform velocity U (plug flow), but the length of the nozzle is sufficient for the laminar flow to become fully-developed before the nozzle exit.

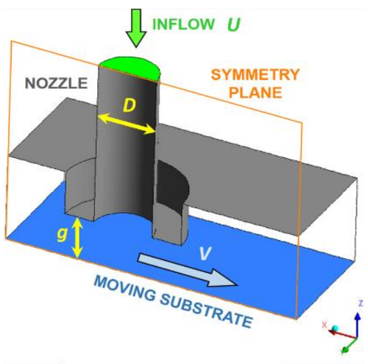

Figure 1. Geometry of the numerical model [8].

The input parameters and the material properties used in the simulations are summarized in Table 1. A parametric study of the rheological parameters was performed, starting with the values reported by Nikzad et al. [9], K = 680 Pa·s^n and n = 0.4.

Table 1. Parameters used in the numerical simulations.

Variable	S.	Unit	Value
Inner nozzle diameter	D	mm	1
Gap distance	g	mm	{0.4, 0.6, 0.8, 1}
Uniform inflow velocity	U	mm/s	20
Substrate velocity	V	mm/s	{10, 15, 20}
Consistency index	K	$Pa \cdot s^n$	{200, 680, 3000}
Power Law index	n	-	{0.2, 0.4, …, 1.0}
Fluid density	ρ	kg/m^3	800
Gravity acceleration	a	m/s^2	-9.81

2.3. Principles of the numerical simulations

The flows were simulated with the software ANSYS® Fluent R18.2 [10]. A tetrahedral mesh was used with a maximum length of the element edge δl=60 µm and a time step of 1 ms. An implicit scheme was chosen to advance the governing equations in time and the coupled volume-of-fluid/level-set method was used to track the surface of the fluid. The simulations were running for 2.5 s before obtaining steady state solutions.

3. Results

3.1. Morphology of the printed filament

The strand's cross-sections monitored at the outlet boundary are shown in Figure 2. The change of viscosity model from the Newtonian fluid to the power-law fluid has a negligeble impact on the shape of the strand cross-section. This observation was confirmed in all the tested printing conditions (see Table 1).

3.2. Printing force

The gauged pressure (relative to the atmospheric pressure) acting on the substrate was normalized by the average viscous stress in the nozzle. This normalized pressure was integrated over the substrate surface in order to obtain the normalized printing force. In Figure 3, the printing force for the Newtonian and the power-law fluids, as a function of printing conditions, are compared. The figure shows that the introduction of a shear-rate dependent viscosity changes the magnitude of the printing force, but not its linear trend with respect to the substrate velocity.

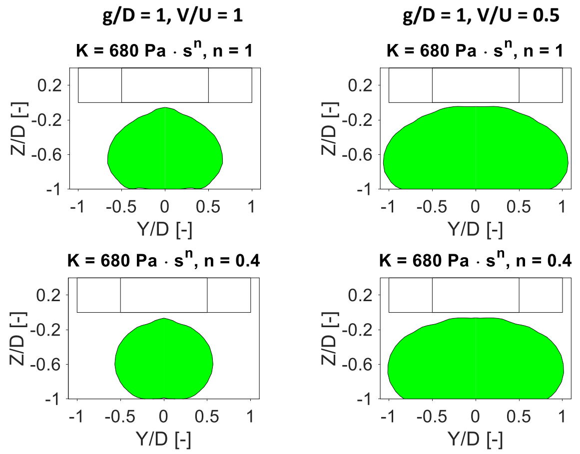

Figure 2. Strand cross-section for the Newtonian (top) and the power-law (bottom) fluids.

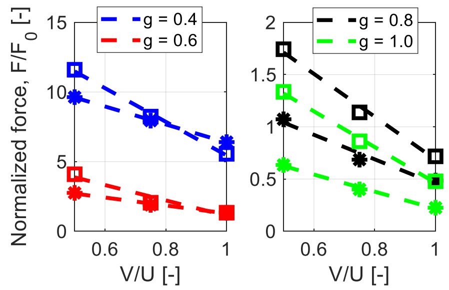

Figure 3. Normalized printing force as a function of the substrate velocity for the Newtonian (stars) and the power-law (squares) fluids.

4. Summary and conclusions

This paper quantifies the influence of shear thinning effect of the molten plastic on the strand deposition during Extrusion-Based Additive Manufacturing. The results show no significant change in the cross-sectional shape of the strand. Moreover, the shear-thinning affects the magnitude of the printing force, but not its linear trend with respect to printing speed. Thus, we conclude that the Newtonian fluid assumption is sufficient to predict the strand cross-section and the order of magnidude of the printing force. However, the results should be treated as a first approximation due to the isothermal process assumption. Further work will be focused on the experimental validation of the numerical model.

References

[1] Turner B. N., Gold S. A., Strong R., 2014, *Rapid Prototyping Journal*, **20**, 3, 192-204.
[2] Bellehumeur C., Li L., Sun Q., Gu P., 2004, *Journal of Manufacturing Engineering*, **6**, 2, 170-178.
[3] Bellini A., Guceri S., Bertoldi M., 2004, *Journal of Manufacturing Science and Engineering*, **126**, 237-246.
[4] Sun Q., Rizvi G.M., Bellehumeur C.T., Gu P., 2008, *Rapid Prototyping Journal*, **14**, 2, 72-80.
[5] Costa S., Duarte F., Covas J., 2017, *Journal of Materials Processing Technology*, **245**, 167-179.
[6] Turner B. N., Gold S. A., 2015, *Rapid Prototyping Journal,* **21**, 3, 250-261.
[7] Rodriguez J. F., Thomas J. P., Renaud J. E., 2000*, Rapid Prototyping Journal*, **6**, 3, 175-186.
[8] R. Comminal, M. P. Serdeczny, D. B. Pedersen, J. Spangenberg, 2018, *Additive Manufacturing*, **20**, 68-76.
[9] Nikzad M., Masood S.H., Sbarski I., Groth. A., 2009, *Tsinghua Science and Technology*, **14**, 29-37.
[10] ANSYS® FLUENT R18.2, ANSYS FLUENT Theory Guide, © ANSYS, Inc, 2017.