FLOW-INDUCED FIBER ORIENTATION DURING MATERIAL EXTRUSION ADDITIVE MANUFACTURING

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Keywords: Extrusion, fiber orientation, single/multi-layer deposition, nozzle shape, corner prints

Introduction

Material Extrusion Additive Manufacturing (MEX-AM) has proven to be highly versatile in its ability to produce both micro components and large-scale structures. This technology has found applications in various industries including medical, construction, aeronautical, and energy sectors [1]. While MEX-AM was originally invented as a novel prototyping technique capable of producing unique and intricate shapes, parts that possess enhanced mechanical and thermal properties are of interest in, e.g., industrial-scale production and applications. One of the simplest ways to achieve this improvement is by incorporating short reinforced fibers, which can significantly increase the thermo-mechanical properties of the produced part. The improvement in thermo-mechanical properties is typically anisotropic and strongly influenced by fiber orientation. As a result, predicting the fiber orientation is a crucial aspect in the performance assessment of the produced part [2]. Having that in mind, our study focuses on analyzing the relationship between flow dynamics and fiber orientation in the MEX-AM process.

Method

The finite volume open-source software OpenFOAM was employed to solve the three-dimensional Navier-Stokes equations coupled with a transport equation of a phase scalar, α, and a second rank orientation tensor, $\mathbf{A}$. The model was two-way coupled, meaning that the fiber orientation was influenced by the flow dynamics, and, in turn, the rheology was dependent on fiber orientation. The coupling back to the anisotropic stress tensor due to the presence of fibers can be written as:

$$\sigma = -p\mathbf{I} + 2\mu(\mathbf{D} + N_p\mathbf{A_{(4)}}\mathbf{D}) \tag{1}$$

where p is the pressure, μ is the apparent dynamic viscosity, $\mathbf{D} = ((\nabla\mathbf{u}) + (\nabla\mathbf{u})^T)/2$ is deformation rate tensor and $\mathbf{A_{(4)}}$ is fourth-rank fiber orientation tensor that requires a closure technique. In this work, common simple closure approximations were used, such as quadratic and hybrid approaches [3]. The influence of fiber on flow dynamics through the stress term in the momentum equation was given through $N_p\mathbf{A_{(4)}}\mathbf{D}$ term, where N_p is the level of anisotropy dependent on the fiber volume fraction, Φ, and the aspect ratio, a_r. The level of anisotropy was defined as [4]:

$$N_p = \frac{\Phi {a_r}^2}{3ln\sqrt{\pi/\Phi}} \tag{2}$$

Finally, the transport equation of the second rank orientation tensor based on the Advani and Tucker macroscopic approach can be written as [5]:

$$\frac{\partial\mathbf{A}}{\partial t} + (\mathbf{u}\cdot\nabla)\mathbf{A} = -(\mathbf{W}\cdot\mathbf{A} - \mathbf{A}\cdot\mathbf{W}) + \lambda_F(\mathbf{D}\cdot\mathbf{A} + \mathbf{A}\cdot\mathbf{D} - 2\mathbf{D} : \mathbf{A_{(4)}}) + 2D_r(\mathbf{I} - 3\mathbf{A}) \tag{3}$$

where $\mathbf{W}$ is a vorticity tensor, λ_F is a fiber shape factor, D_r is a rotary diffusion coefficient describing the fiber-fiber interactions.

Results and conclusions

We found that fibers in the material matrix tended to be highly oriented in the printing direction during the extrusion/deposition process, but this was concluded to be strongly dependent on the printing conditions. Here, factors such as the extrusion/nozzle speed ratio and nozzle shape influenced the fiber orientation. Additionally, differences in the fiber characteristics, such as the volume fraction and aspect ratio, affected the flow conditions and altered the shape of the printed strands. Further, we found that our observations made for single-layer structures did not always hold true for multiple strands, as fibers can reorient during subsequent depositions. We concluded that this was because printing onto a semi-wet structure deformed the layers, changing their fiber orientation. Our main findings and conclusions are summarized in Figure 1.

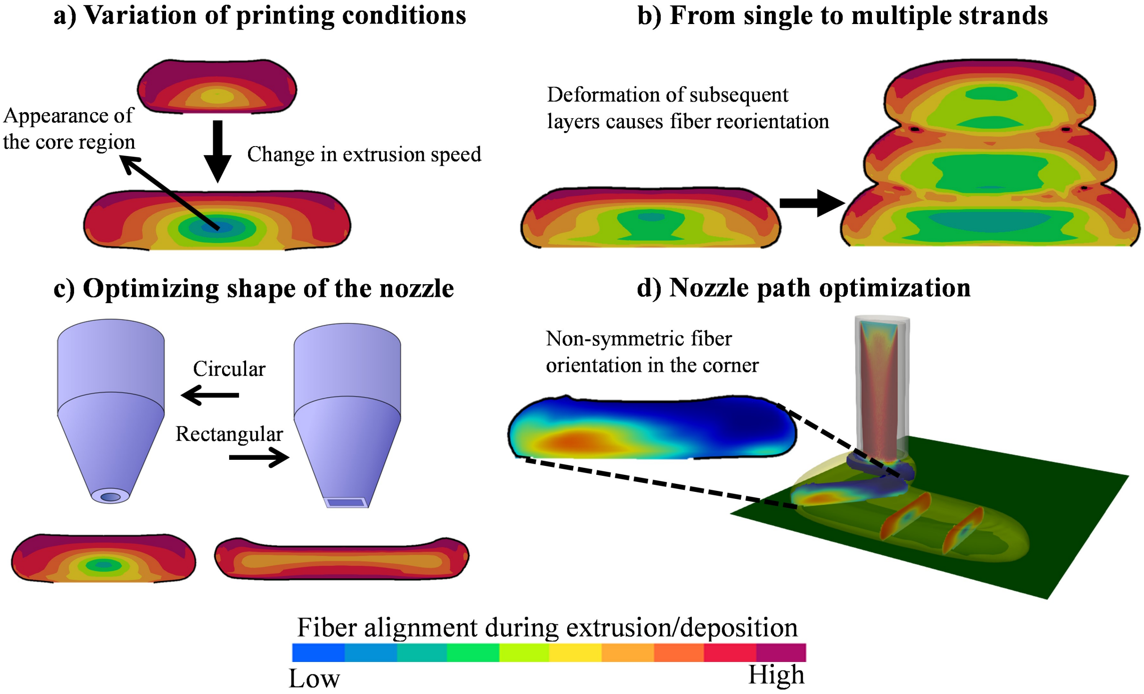

Figure 1: (a) Influence of printing conditions greatly affected the fiber orientation within single strands, also when (b) multiple layers were printed. (c) The geometry of the nozzle not only impacted the shape of the strand but also the fiber orientation to a great extent. (d) Printing curvatures, such as corners, provided a non-symmetric fiber orientation which can be used for nozzle toolpath optimization.

Acknowledgements

The authors would like to acknowledge the support of the Innovation Fund Denmark (Grant no. 0223-00084B). The research is in part supported by the US Department of Energy (DOE), Office of Energy Efficiency and Renewable Energy, Advanced Manufacturing Office, under contract DE-AC05-00OR22725 with UT-Battelle LLC.

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