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Investigation of Fiber Orientation in Screw-based Composite Additive Manufacturing Processes

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Abstract

As industrial advancements progress, additive manufacturing has gained significant interest in both academic and industrial sectors. Among its methods, screw-based material extrusion offers versatility by utilizing pellet-form materials, enabling the processing of thermoplastics like polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS), as well as fiber-reinforced composites such as carbon fiber-reinforced polymer (CFRP) and glass fiber-reinforced polymer (GFRP). Despite its benefits, composite additive manufacturing faces challenges such as reduced quality and mechanical performance, often due to layer bonding issues and irregular fiber orientation. This study addresses fiber orientation irregularities by proposing a predictive model based on the Fiber Orientation Tensor method, integrating rheological behavior inside the nozzle with processing parameters like nozzle size and extrusion speed. Using polyethylene terephthalate glycol (PETG) reinforced with 20 wt% short carbon fibers (sCFRP), the results confirmed that the model accurately predicts fiber orientation, validated through experimental data.

screw based additive manufacturing, composite, fiber direction

1. Introduction

With recent industrial advancements, additive manufacturing (AM) technology has garnered significant attention in both academia and industry. In particular, screw-based material extrusion offers cost efficiency and the capability for large-scale component fabrication by utilizing pellet-form raw materials. This method can process a wide range of materials, including thermoplastics such as ABS and PLA, as well as fiber-reinforced composites like CFRP and GFRP. However, challenges such as quality degradation and reduced mechanical properties often arise due to irregular fiber orientation in additive manufacturing processes.[1-4]

This study analyzes the rheological characteristics within the nozzle during the material extrusion process and predicts fiber orientation using simulations and experimental validation. The core hypothesis is that the rheological behavior at the nozzle tip significantly influences the fiber orientation after deposition. Using ANSYS Polyflow and Python-based open-source tools, a fiber orientation tensor model was developed and analyzed, with experimental data serving as a basis for validation.

2. Proposed Method

In this study, the rheological characteristics inside the nozzle were analyzed to predict fiber orientation under various process conditions in the material extrusion additive manufacturing process. The primary objective was to accurately predict fiber orientation within fiber-reinforced polymer composites after deposition, as it plays a crucial role in determining the mechanical properties of the final product.

The key hypothesis of this research is that the rheological properties at the nozzle tip significantly affect fiber orientation after deposition. To validate this, ANSYS Polyflow was used to integrate rheological characteristics with the fiber orientation tensor model, followed by experimental verification to ensure accuracy. This approach enables a more precise understanding of how material flow influences fiber alignment during extrusion.

The fiber orientation tensor model was implemented using a Python-based open-source library, which serves as the core system for fiber orientation modeling and experimental data validation. By leveraging computational simulations and physical experiments, this study provides valuable insights into optimizing fiber alignment for enhanced composite performance. The overall research methodology is summarized in Figure 1.

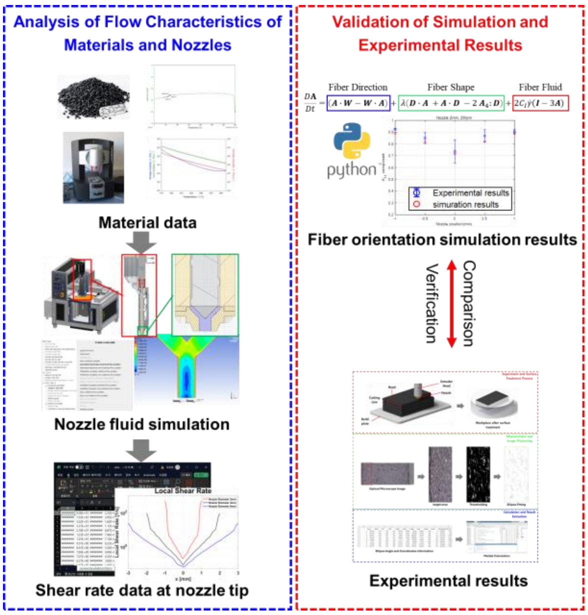


Figure 1. Overview of the Proposed Method

2.1. Rheological Behavior Simulation within the Nozzle

The rheological characteristics at the nozzle were analyzed using ANSYS Polyflow under the following boundary conditions. The composite material was assumed to be incompressible, with no mass loss, and external forces were neglected. The analysis was conducted under isothermal conditions. Based on the experimental system, the shear rate at the nozzle tip was extracted while considering the fluid rotation. This shear rate data was then utilized to predict fiber orientation.

The analysis results are presented in Figure 2, where the X-axis represents the nozzle size-to-X ratio. As observed in the figure, an increase in nozzle size leads to variations in the shear rate inside the nozzle due to wall effects.

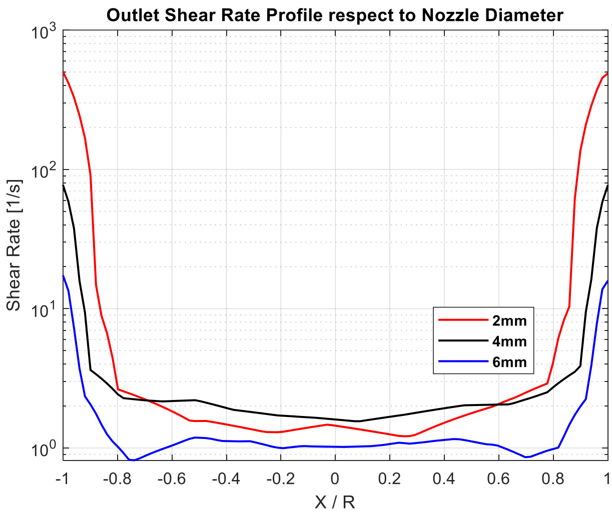


Figure 2. Shear Rate Distribution at the Nozzle Tip

2.2. Fiber Orientation Tensor

To predict fiber orientation, the Folgar-Tucker model, one of the Fiber Orientation Tensor models, was applied. The governing equation for this model is summarized in Equation 1.[5]

$$\frac{D\boldsymbol{A}}{Dt} = (\boldsymbol{A}\cdot\boldsymbol{W} - \boldsymbol{W}\cdot\boldsymbol{A}) + \lambda(\boldsymbol{D}\cdot\boldsymbol{A} + \boldsymbol{A}\cdot\boldsymbol{D} - 2\boldsymbol{A}_4 : \boldsymbol{D}) + 2C_I\dot{\gamma}(\boldsymbol{I} - 3\boldsymbol{A}) \quad (1)$$

In this study, $\boldsymbol{W} = ((\nabla\boldsymbol{u}) - (\nabla\boldsymbol{u})^{\mathrm{T}}) / 2$ represents the vorticity tensor, which describes the rotation of the fluid. CI is the fiber-fiber interaction coefficient, and $\dot{\gamma}$ is based on the shear rate. Additionally, λ denotes the fiber shape factor, and I represents the identity tensor.

As shown in Figure 3, the Fiber Orientation Tensor method represents fiber orientation using a 3×3 matrix. In this tensor representation, the sum of the diagonal elements is defined as 1. As illustrated in Figure 3, when fibers are perfectly aligned along the principal axis (1-axis), the a_{11} component of the matrix equals 1, indicating that all fibers are oriented 100% in the same direction, while the remaining diagonal elements are 0. Conversely, if the fibers are randomly distributed, the diagonal components a_{11}, a_{22}, and a_{33} take values of 1/3, indicating an even 33.33% distribution along the 1, 2, and 3 directions.

To approximate the fourth-order tensor ($\boldsymbol{A}^4$) from the second-order tensor ($\boldsymbol{A}$), a closure approximation method was employed. In this study, the Hybrid[6] closure approximation was applied. Among various closure methods, the fundamental approximation method was chosen, as the primary focus was to determine whether fiber orientation prediction was feasible based on shear rate at the nozzle tip. The aspect ratio (λ) of the fiber, defined as the ratio of fiber length to diameter, is expressed as follows:

$$\lambda = \frac{{a_r}^2 - 1}{{a_r}^2 + 1} \quad (2)$$

The fiber-fiber interaction coefficient (C_I) is an empirical constant. According to previous studies, the recommended range for this coefficient is $0.0001 < C_I < 0.016$[7-9]. The short carbon fiber-reinforced polymer (sCFRP) used in this study has an average fiber length of 250 µm and a diameter of 7 µm. Based on these values, the fiber-fiber interaction coefficient was set to 0.01.

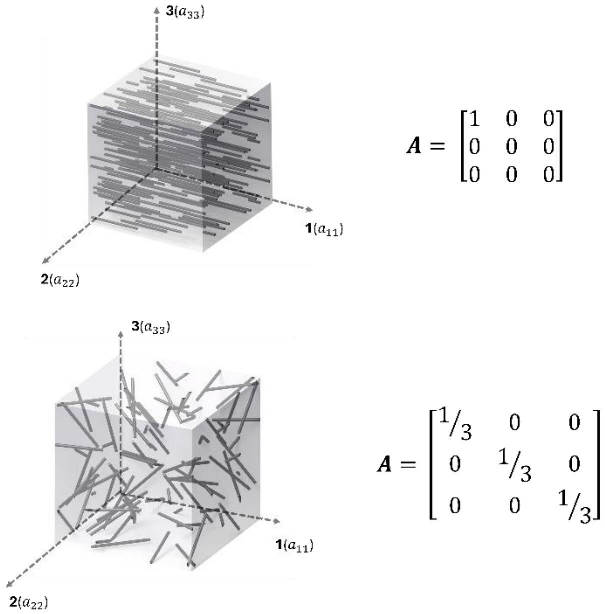


Figure 3. Shear Rate Distribution at the Nozzle Tip

3. Experimental Setup

The experimental setup is illustrated in Figure 4. It was developed for lab-scale experiments and operates using a gantry-type system. The material used in the experiment was PETG + sCFRP (20 wt%), supplied by Samyang Corporation. The detailed material properties, including tensile strength, tensile elongation, flexural strength, impact strength, and heat deflection temperature, were provided by Samyang Corporation based on their internal testing and are summarized in Table 1.

This experiment was designed to analyze fiber orientation based on nozzle size by setting three different nozzle size levels. The experimental conditions are presented in Table 2.

Figure 4. Experimental Setup

Table 1 Material Information

Material	PETG + sCFRP(20wt%)
Tensile strength	100 MPa
Tensile elongation	4 ~ 5 %
Flexural strength	120 MPa

Impact strength	10 kgf·cm/cm
Heat deflection temperature	150 °C
Fiber length	250 μm
Fiber diameter	7 μm

Table 2 Experimental Conditions

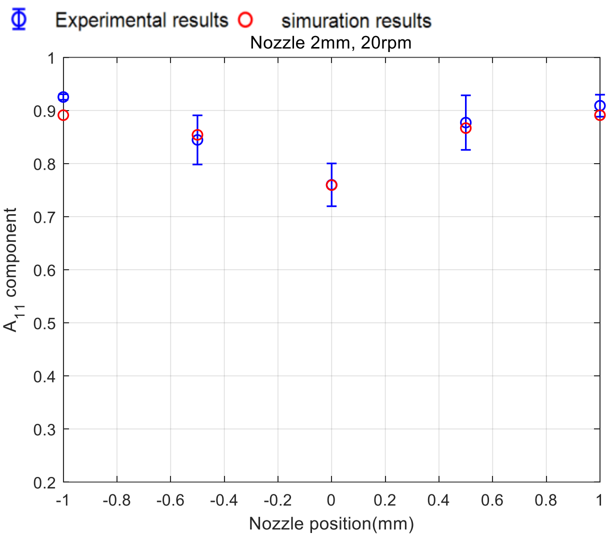
Parameters	**Values**		
Nozzle Diameter(mm)	2	4	6
Extruder Speed(rpm)	20		
Printing Width(mm)	2.1	4.2	7.1
Printing Height(mm)	1.5	3	4
Printing Speed(mm/min)	1,680	480	222

4. Simulation and Experimental Results

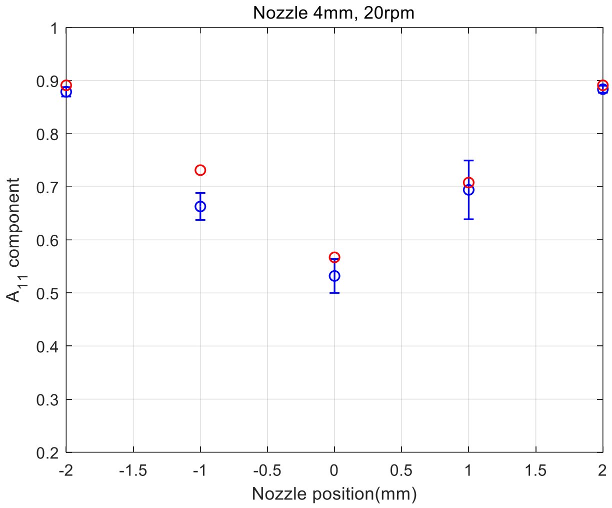
The experimental and simulation results based on nozzle size are presented in Figure 5. The experimental results were obtained by repeatedly measuring the analysis area and are represented with error bars. The blue circles indicate the mean values within the error bars. The error rates of the proposed method are summarized in Table 3.

Figure 5(a) shows the experimental and simulation results for a nozzle diameter of 2 mm at an extrusion speed of 20 RPM. The results indicate a general agreement between the experiment and simulation, with variations at specific positions represented by error bars. Figure 5(b) presents the results for a 4 mm nozzle diameter, while Figure 5(c) illustrates the results for a 6 mm nozzle diameter, both at an extrusion speed of 20 RPM. In each graph, the blue circles represent the average values of the experimental results, and the error rates were derived by comparing them with the simulation results.

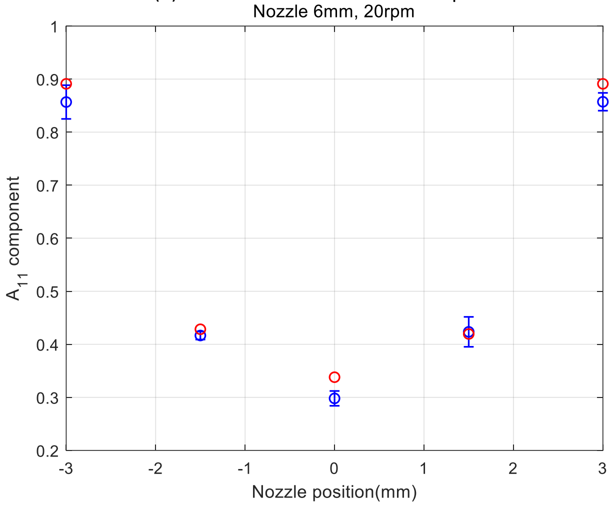
Table 3 summarizes the error rates for each experimental condition, showing the error rates between the mean experimental values and the simulation results. The error rates varied depending on nozzle size and extrusion speed, with 1.6% for the 2 mm nozzle, 4.2% for the 4 mm nozzle, and 5.0% for the 6 mm nozzle. These results confirm the high accuracy of the proposed method.



(a) Results for 2 mm Nozzle at 20 rpm



(b) Results for 4 mm Nozzle at 20 rpm



(c) Results for 6 mm Nozzle at 20 rpm

Figure 5. Experimental and Simulation Results

Table 3 Error Rates between Experimental and Simulation Results

Nozzle Size(mm)/Extrusion Speed(rpm)	**Error Rate (%)**
2 mm / 20 rpm	1.6
4 mm / 20 rpm	4.2
6 mm / 20 rpm	5.0

5. Conclusion

This study focused on predicting fiber orientation based on nozzle size, and the results are summarized as follows. The experimental and simulation results for different nozzle sizes (2mm, 4mm, and 6mm) showed an overall agreement. The error rates between the experimental and simulation results were 1.6% for the 2mm nozzle, 4.2% for the 4mm nozzle, and 5.5% for the 6mm nozzle. According to previous studies, there is a lack of experimental and validation data, and further research is needed to predict fiber orientation while considering the material extrusion process system. The proposed method in this study demonstrated a general agreement with the experimental results, achieving an average prediction accuracy of 97%.

Therefore, the fiber orientation prediction method considering the rheological characteristics inside the nozzle was found to have high accuracy. It was also confirmed that the rheological properties at the nozzle tip significantly influence the fiber orientation in the deposited material. Additionally, as the nozzle size increased, the prediction accuracy showed a decreasing trend, which is attributed to the presence of voids in the material cross-section, leading to reduced accuracy. In conclusion, the proposed method achieved an average fiber orientation prediction accuracy of 97%, which is expected to contribute to enhancing mechanical properties and improving material quality by optimizing fiber orientation. Future research will extend this approach to predict fiber orientation under various process parameters, further refining the accuracy and applicability of the model.

Acknowledgment

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