Title:
Numerical Study of Non-Newtonian Ceramic Slurry Flow in Extrusion-based Additive Manufacturing

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Introduction:
Additive manufacturing (AM) is a process having a bottom-up approach where the material is added layer by layer using a predetermined three-dimensional (3D) toolpath with defined process parameters to obtain the final product with minimal material waste. Extrusion-based additive manufacturing (EAM) processes are widely used for 3D object fabrication due to their reliability and the diversity of the material being used. The use of ceramics as a raw material is still in its nascency. Major challenges in the EAM of ceramics include the preparation of feedstock slurry and its flowability through an extruder, which plays a crucial role in the 3D printing of defect-free parts. Numerical simulation can predict the approximate outcome of complexities arising during experimentations. For non-oxide ceramic slurry in EAM, primarily experimental and analytical works have been reported, while no literature predicted the process outcome using numerical analysis.

This paper focuses on the development of a numerical model that simulates the non-Newtonian ceramic slurry flow through the nozzle of a customized cartesian 3D printer. The focus of the work lies in the implementation of the Herschel-Bulkley Papanastasiou (HBP) model for feedstock slurry to understand the behavior inside the nozzle for the uniform flow through the nozzle. A rotating viscometer is used to measure the viscosity of the slurry. The observed value is used as an input for measuring the rheological constants of the ceramic slurry. The rheological constants for the HBP model are compared with the Power-law model and Bingham plastic model to validate the best-fit model for the ceramic slurry. The variation of velocity of slurry across the length of the nozzle and surface pressure is analyzed through numerical simulation. The results are identified based on the flow behavior of ceramic slurry at different sections over the length of the extruder. The significance of inlet velocity over the printing velocity is examined. Besides, the effect of temperature on the extruder and the fluid flow is investigated with the help of numerical simulation. Further, the time-dependent study is performed to understand the effect of temperature distribution when the ceramic slurry is flowing through the extruder.

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Main Idea:
The modelling and numerical simulation were required to upgrade the Creality Ender-3 3D printer to deposit and manufacture ceramic parts. Fig. 1(a) shows the customized 3D printer setup where the stepper motor is connected with a lead screw to feed the slurry in the extruder. Fig. 1(b) shows the section view of the extruder. The extruders consist of different parts such as the throat, heating block, nozzle, heat sink, and pneumatic connector. The nozzle geometry with throat and slurry is exported to COMSOL Multiphysics as illustrated in Fig. 1(c). The model is designed and implemented as a 3-dimensional geometry, where the throat and nozzle are modeled as a contact assembly. The study is limited to the geometry of the throat and nozzle, where the cross-section varies from the inlet of the throat to the outlet of the nozzle.

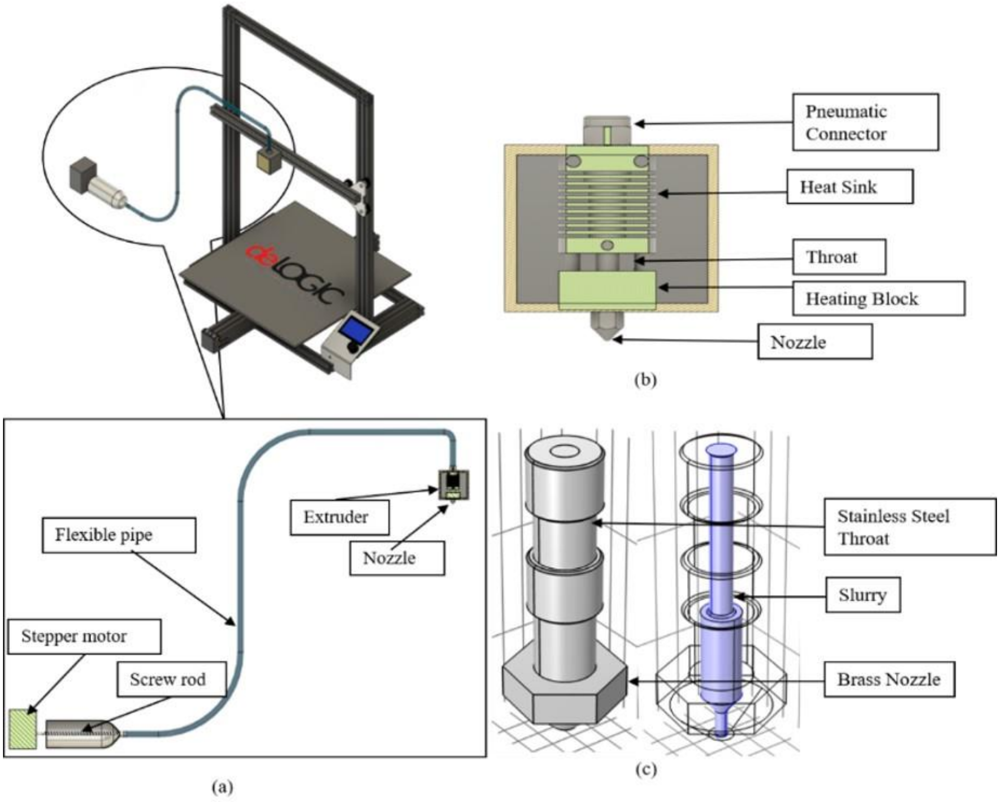

Fig. 1: Customized 3D Printer setup (a) Extrusion System (b) Extruder (c) Geometry of nozzle and slurry.

Boron carbide (B_4C) ceramic of 99% purity with 220 mesh size and methylcellulose (MC) of high viscosity grade as a binder were chosen for the experimental calculations of viscosity and numerical simulations in this work. The ceramic-cellulose slurry, which passes through a small diameter of the nozzle, shows non-Newtonian behavior and shear thinning characteristics due to low shear rates [1]. Power Law (PL), Bingham Plastic (BP), and the Herschel-Bulkley model can be used to study the shear rate behavior of ceramic slurries. Papanastasiou presented a modified Herschel-Bulkley model equation to relate strain rate tensor (D) with viscous stress tensor (τ) [2]. Due to a wide range of shear rates, the modified Herschel-Bulkley model, also known as the Herschel-Bulkley Papanastasiou (HBP) model, was implemented in this work. To determine the flow index, fluid consistency index, and yield stress of slurry, an algorithm was developed and implemented in MATLAB. Fig. 2 shows the flowchart of the MATLAB code. The rotating viscometer was used to measure the dial gauge reading of the ceramic slurry with the corresponding RPM. The algorithm takes the measured data as input in a .xlsx format. Before

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further processing, the data files are arranged and labelled according to the measured values and simultaneously checked for errors or missing data in columns. Further, the dial gauge values, and RPM were converted into shear stress and shear rate using the conversion formulations. The newly converted data is updated in the new .xlsx file. The updated data is plotted as shear stress vs shear rate. Power law (PL), Bingham plastic (BP) and Herschel Bulkley Papanastasiou (HBP) numerical models were used to calculate index values using curve fitting functions and performing multiple iterations. The best-fitted coefficients are determined and shown in Fig. 3.

The slurry flow from the inlet of the throat to the exit of the nozzle was assumed to be the laminar flow. The throat and nozzle were filled with the slurry without any void formation, and it was considered an incompressible flow. The slurry does not experience the slip at the wall of the nozzle. The ambient temperature was considered at the inlet of the throat as well as at the outlet of the nozzle. A time-dependent study was performed to understand heat transfer in solid and fluid, while a stationary study was performed to understand the slurry flow behavior.

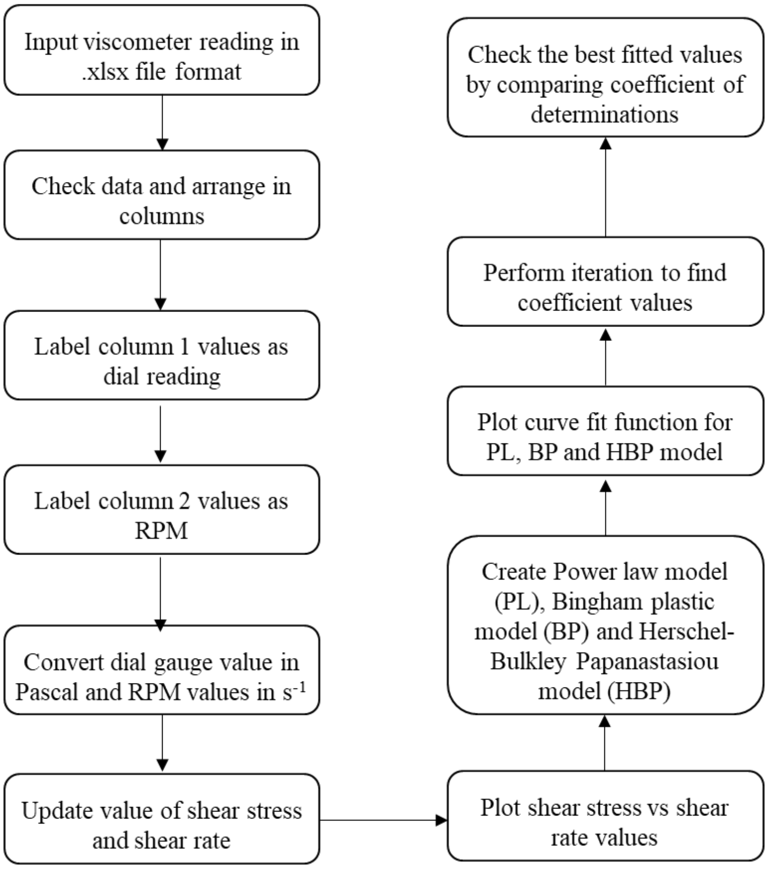

Fig. 2: Flow chart to determine rheological constants and the best-fitted computational model.

A time-independent study was performed to understand the applied HBP model for the slurry flow simulation. Figure 4(a) shows the velocity variation of ceramic-cellulose slurry across the length of the throat and nozzle at a temperature of 220 °C. The laminar flow and heat transfer modules are coupled to calculate the exit velocity and velocity variation across the length of the non-constant temperature. The velocity is constant and uniform across the throat region, while the velocity increases significantly across the conical region due to a decrease in the cross-section area. The maximum predicted exit

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velocity is 44 mm/s with 56 wt% solid loading in slurry. This exit velocity can be increased with an increase in water content in the slurry. The nozzle geometry is divided into 3 sections to understand the flow behavior. Force acting on the slurry due to changes in the cross-section area of different sections contributes to the occurrence of surface pressure. Figure 4(b) demonstrates the surface pressure distribution across the length of the slurry due to solid-fluid interaction. The maximum surface pressure is found at the throat's inlet. Due to varying conical sections, the slurry decomposes into radial and transverse components. The surface pressure drops as it approaches the nozzle outlet due to the force applied by the wall of varying conical sections.

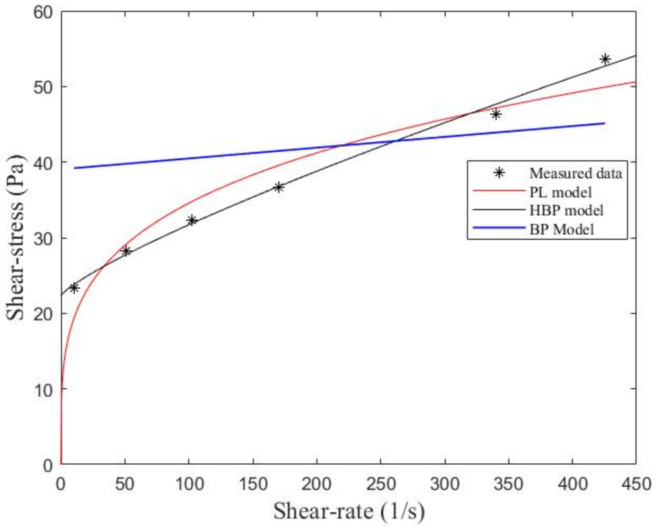

Fig. 3: Comparison of different computational models to find the best-suited model.

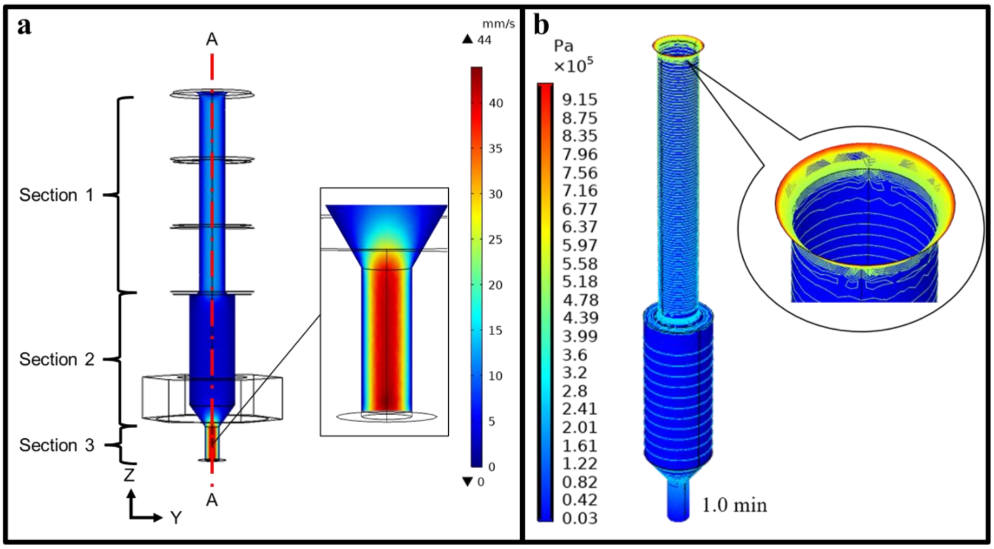

Fig. 4: (a) Variation of velocity across the length of the nozzle and (b) Surface pressure on slurry throughout the length of throat nozzle assembly.

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Conclusions:

This work proposes a numerical model to simulate non-Newtonian ceramic slurry in the Extrusion-based additive manufacturing (EAM) process. The computational model is established to find the rheological constants of HBP models. The computational model will be valid for oxides as well as non-oxides ceramics based on the input viscometer readings. The HBP numerical model predicts the velocity distribution from the throat inlet to the nozzle outlet. It was observed that the exit velocity of the slurry is more influenced by input pressure rather than the temperature due to the content of solid ceramic particles in the slurry and the high melting temperature of the ceramic material. The effect of change in the cross-section area in geometry shows significant effects on the surface pressure of the slurry. Further, the higher temperature at the throat achieves better flowability due to the melting of the binder material of the slurry.

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