Title:
Numerical Analysis of Progressive Cavity Pump Extruder for 3D Printing of High Viscosity Ceramic Paste

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Introduction:
Additive manufacturing (AM) or 3D printing is a novel toolless additive manufacturing process where a solid three-dimensional object is printed from a digital file. In this process, the materials are added in successive layers to shape the final 3D object thereby reducing the wastage of material and hence tooling cost. Earlier, AM techniques were considered suitable only to produce the form, fit, and in very limited cases, functional prototypes. In today's time, the precision, repeatability, and material range of 3D printing have increased to a great extent. AM processes are categorized into 7 different families according to ASTM-F2792 standards. These are Vat Photopolymerization, Powder Bed Fusion, Binder Jetting, Material Jetting, Sheet Lamination, Material Extrusion, and Direct Energy Deposition. Material extrusion, being one such family of AM processes, can produce parts with good structural properties and is cost-efficient. One of the most widely used processes in the present times is the Material Extrusion process, where the granules are softened and melted by employing heat and they are then pushed mechanically through a die. Pushing the soft material through the die will cause it to form a continuous filament strand of the diameter of the die orifice. Fused Deposition Modeling (FDM) and Direct Writing Assembly (DWA) are the types of Material Extrusion processes. Three types of extruders are used in material extrusion additive manufacturing technologies. Those are filament-fed extruders, screw extruders, and syringe extruders. The screw extruder has advantages such as lower cost, higher speed, and a wide range of materials that can be utilized. The screw extruders use the raw materials either in solid pellets/granules form or in the molten state. The granule-based extrusion processes can be categorized into two types, i.e., continuous and discontinuous. In continuous extruders, a rotor is used to extrude a continuous material deposition, whereas discontinuous extruders, also called batch extruders, are suitable for short-burst operations like injection moulding. They use rams, like in the form of syringe extruders, to press out the materials. There are various types of continuous polymer extruders like single screw extruders, multi-screw extruders, viscous drag extruders, and elastic melt extruders. The discontinuous polymer extruders are classified as ram extruders and reciprocating single-screw extruders. Progressive Cavity Pump is one such screw extruder that has several advantages over other pumps, such as providing a uniform flow rate without any pulsation, the capability of pumping very light liquid to very pasty fluids, the absence of check valves, and no need of liquid as a

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primer to start the pump. Progressive Cavity Pump (PCP) is a special case of Moineau pump, which has the ability to pump thick products without spoilage. In other words, the PCP transfers fluid by means of progress, a sequence of small, fixed shapes and discrete cavities, as the rotor turns.

Different methods used by researchers for extruder design and discrete element simulation were analyzed, and various types of extruders and their types are explored. A volumetric mini extruder was developed for pellets or granules of recycled plastic that can be used in a RepRap FDM 3D printer for rapid prototyping [1]. The most commonly used pneumatic extrusion process was compared to a miniaturized progressive cavity pump in terms of its accuracy and precision as well as the compatibility of the extrusion process with bioprinting [2]. Hong et al. developed a screw extruder printer and the copper (Cu) paste was extruded through it. The article mainly presented the content related to Cu paste and the percentage of Cu to be utilized to maintain a specific viscosity [3]. Orisaleye et al. [6] developed a mathematical model to design a screw extruder with consideration for processing Non-newtonian biopolymers. An analytical solution is attempted for the flow of a slightly Non-newtonian shear-thinning material in the screw extruder. Orisaleye and Ojolo [7] carried out the parametric study of solids compaction in the single screw extruder to aid the design of a straight screw extruder for biomass compaction and related applications. The impact of FDM process parameters on the strength of fabricated parts was assessed using Taguchi's design of experiments (DOE) [9]. The filament feeding force was experimentally investigated, as a function of the feeding rate for different materials (PLA and ABS), liquefier temperatures, nozzle diameters, and lengths of the liquefier. Two extrusion regimes were identified, i.e., a linear regime with a stable flow, and a non-linear regime with fluctuations in the feeding force, which are concomitant to unstable extrusion [8].

The research fraternity has reported the simulation of the flow of high-viscosity paste of ceramic material in a PCP extruder [5]. However, the influence of flow parameters on the extrusion of ceramics with PCP had not been compared with the conventional extrusion process of the ceramic paste. This has led to poor analysis and inadequate prediction of output flow rate. Moreover, no work to date had reported the dependency of various input flow parameters of PCP on the flow rate during extrusion. The purpose of this investigation is to assess the dependency of the flow characteristics of ceramic paste on different processes and geometric parameters of the PCP. For that, the flow must be studied as it happens, i.e., lab-scale, or else it needs to be simulated. The three-dimensional vector theory and the theory of hypocycloid were developed, which are used to provide a new modeling insight into the design and performance of PCP [4]. The numerical study of various extruder designs for ceramic materials and their paste is yet to be explored comprehensively by the active research community.

Main Idea:

The main objective of this research is to perform the Computational Flow Dynamics (CFD) simulation of the flow of ceramics paste in the progressive cavity extruder in the 3D printing process. Since literature does not report flow visualization of the material as it passes through the length of the extruder, it would be very helpful to develop such a technique, as it can reduce the cost and efforts of performing experimental or mathematical tests for each design of the extruder. The process parameters for the numerical simulation of paste flow in PCP are inlet pressure, rotational speed of the rotor, output velocity, and output pressure of the paste. The simulation results can be obtained in the form of the output velocity of the materials, which can be further used to find the flow rate at the output. The numerical simulation can also be used to test the effect of input parameters on the output and can lead to optimizing the design of the extruder. Since the ceramics 3D printing process is gaining wide acceptability, insight into its flow and investigating the dependency of flow on the physical characteristics of ceramics would give a clear understanding of the process. Also, it would help to compare the flow of paste in a PCP with that of the extrusion process for the same ceramic paste.

Initially, geometric and solid modeling of the PCP is carried out. As a part of geometric modeling, the Hypocycloid model of the PCP is studied. Further, a 3D vector approach is used for modeling and analyzing the profile of the PCP [5]. The flow rate at the outlet of PCP is formulated in terms of geometric parameters of PCP, i.e., stator pitch, rotor pitch, number of lobes, eccentricity, and rotational speed of the rotor. The effect of the number of lobes and rotational speed of the rotor on the output flow rate was studied and it is further compared with the existing reported work using MATLAB [5]. Based on these results, the solid model of the PCP is generated with the geometric parameters of PCP, which yields

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the maximum output flow rate. The profile generated, by using the hypocycloid model, helps model a 3-dimensional (3D) profile of the progressive cavity pump. A solid working model of the PCP, as shown in Fig. 1, has been developed in SOLIDWORKS.

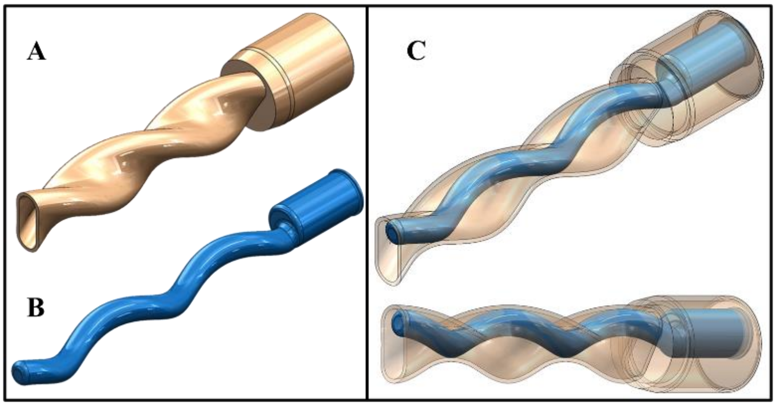

Fig. 1: (A) Stator, (B) Rotor, and (C) Assembly of PCP.

The computational fluid dynamics (CFD) technique is used for the flow simulation of paste. The numerical simulation workflow involves the spatial discretization of the simulation domain by building a grid or mesh. The tetrahedral mesh is used for the assembly as they fit very well for any arbitrarily shaped geometry with their simple computations. PLA paste is simulated initially for the validation of the PCP model. The pressure and velocity are found to be constant throughout the PCP without any discontinuity and break in the flow. Therefore, the PLA paste flow model confirms the continuous flow inside the designed model of PCP. The CFD technique is further utilized for the numerical simulation of ceramics paste through the PCP extruder. At first, the ceramic paste of earthenware is simulated inside the PCP, and the flow simulation results are compared with the results of the extrusion process. Further, alumina paste is simulated in the PCP to find the variation of exit velocity of alumina at different rotor speeds of PCP. Fig. 2(A) shows the velocity distribution of alumina inside PCP at an inlet pressure of 2 MPa and Fig. 2(B) shows the velocity distribution of alumina inside PCP at 30 RPM of the rotor.

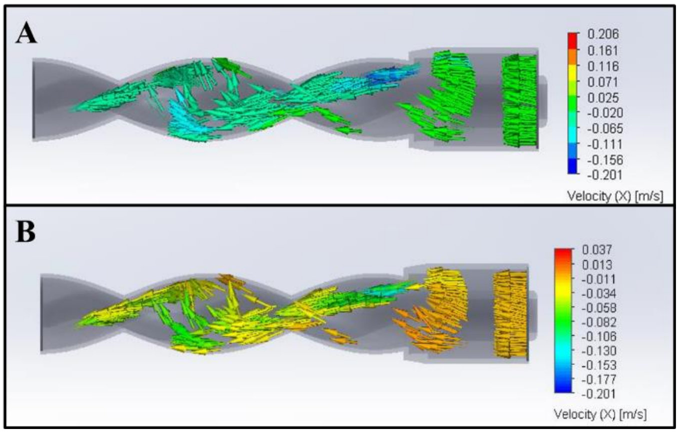

Fig. 2: Velocity distribution of ceramic material (alumina) inside PCP (A) at inlet pressure of 2 MPa, (B) at 30 RPM of the rotor.

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Conclusions:

In the present work, a 3D hypocycloidal model of a progressive cavity pump for the extrusion of ceramics for 3D printing is analysed. The equations related to the design of PCP are validated in MATLAB. Based on these results, the geometric parameters of PCP are chosen such that the maximum output flow rate is achieved at the outlet of PCP. Using these geometric parameters, the solid model of PCP is developed in SOLIDWORKS. Initially, the CFD technique is used to simulate the flow inside PCP for PLA paste. It is observed that the pressure and velocity of PLA are constant throughout the PCP during the flow simulation. Therefore, it can be concluded that the PLA paste flows smoothly without any clogging or discontinuity. Thus, the paste flow model of PLA in PCP is validated. Further, the flow of paste in PCP is compared with the flow of paste in the extrusion process for earthenware ceramic material. The results of the simulation show that the exit velocity of earthenware paste is increased in PCP in comparison to the extrusion process for the same inlet conditions. This is because the rotation of the rotor plays a vital role in increasing the pressure of the paste in addition to the inlet pressure of the paste. This increase in pressure causes the paste to flow at a higher velocity in PCP. Therefore, the higher exit velocity of earthenware paste is obtained in PCP than in the extrusion process. This would also result in a higher printing speed when PCP is used in the 3D printing process. Further, the work is extended to understand the variation of the output flow velocity of alumina paste for the varying rotational speed of the rotor. This leads to getting an insight into the flow characteristics of alumina and the control over the flow of alumina in the 3D printing process.

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