Analysis of Screw Extrusion of Thermoplastics for AM

Yash Gopal Mittal (ymymittal1@gmail.com)  
Indian Institute of Technology Bombay  https://orcid.org/0000-0001-7790-2334

Shivam Prajapati  
National Institute of Technology Agartala

Pushkar Kamble  
Indian Institute of Technology Bombay

Dmitriy Trushnikov  
Perm National Research Polytechnic University: Permskij nacional'nyj issledovatel'skij politehniceskij universitet

Alain Bernard  
EC Nantes: Ecole centrale de Nantes

Karunakaran K. P.  
Indian Institute of Technology Bombay

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Abstract

3D printing is an Additive Manufacturing (AM) process that enables physical realization of a CAD (Computer-Aided Design) model. 3D printing can be classified into several variants; Material Extrusion Additive Manufacturing (MEAM) is the most versatile and widely used. MEAM is a continuous extrusion and selective deposition process commonly used for thermoplastics. Screw Extrusion Additive Manufacturing (SEAM), a sub-domain of MEAM, uses an extruder screw to push the polymer-melt out of the nozzle. Computational Fluid Dynamics (CFD) analysis of a single screw extrusion of thermoplastics is presented in this paper. The effect of various control parameters like screw rotation, wall heat flux/temperature profile, screw geometry, etc., has been studied on the required output parameters like productivity, torque capacity, power requirement, metering efficiency, etc. It is found that the incrementally-variable-pitch screw geometry provides the best metering characteristics. However, every screw design is a compromise between melt temperature, productivity, and power requirements.

Keywords-3D printing/ CFD/Filament Extrusion/Single Screw Extrusion/Thermoplastics

Introduction

Piston extrusion is a standard extrusion technique where the material extrusion is controlled by the piston's reciprocating motion placed inside the cylinder. Piston extrusion is intermittent, as the material extrusion occurs during the forward stroke only. Piston extrusion systems offer better flow control but low output rates as compared to continuous extrusion.

Screw extrusion is a continuous extrusion process where a steady conversion of material phase happens, starting from thermoplastic polymer grains to polymer-melt extrusion. The primary element is the extruder screw that pushes the grains forward. The grains are then melted using external heaters and extruded out of the nozzle.
attached at the end. Screw Extrusion Additive Manufacturing (SEAM) is a versatile process for polymer material deposition for 3D printing applications. It offers material flexibility and provides escalated outputs.

Validation of any process is essential for determining the process capabilities and optimized conditions. Theoretical modeling, supported by computational analysis and validated by physical experimentation, is necessary to complete a process. Finite Element Analysis (FEA) techniques are used for computational analysis of the screw extrusion process. FEA discretizes the domain of interest by subdividing it into smaller and simpler parts, called finite elements, followed by meshing over the domain. A given set of boundary conditions (BCs) formulates the system into algebraic equations, which approximates the unknown functions over the domain[4].

The simpler algebraic formulations that model these final elements are then assembled into a more extensive set of system equations that models the entire problem. Minimization of the associated error functions is a criterion for solution convergence. Computational Fluid Dynamics (CFD) based FEA is done on the screw extrusion process. CFD is a fluid mechanics branch that deals with fluid flow analysis using numerical analysis. CFD is a helpful tool for fluid flow analyses and is employed to handle problems having the concept of non-Newtonian rheologies such as thermoplastic polymer-melt flow. Effects beyond fluid mechanics such as multi-phase flow, static forces, thermal analysis, and heat flow are also incorporated in CFD modelling.

In SEAM, CFD analysis provides the strategy for the optimal solutions to get the desired multi-variable outputs. Various research has been done in the domain of screw extrusion to optimize the process parameters for the defined problem and stated applications[5,6]. Baalaganapathy et al. presented a study on the CFD simulation of single-screw extruders used in cable industries. The feasibility of using CFD models for designing plastic extrusion devices is shown[7].

In this research, the effect of various process parameters on the polymer-melt flow inside a single screw extruder for 3D printing applications is investigated using commercial CFD packages. Geometrical and process parameters such as screw flight geometry, melt temperature distribution, screw rotation, etc., are analyzed for optimum output conditions, considering extrusion velocity, metering pressure, and torque capacity. This CFD analysis provides a strategy for optimum material extrusion conditions leading to enhanced output, flow metering, and thermoplastic polymer-based SEAM power requirements.

**Materials and Methods**

1. **Single Screw Extrusion**

Single screw extrusion is a continuous process where thermoplastic grains are heated and extruded ceaselessly. Various thermoplastics such as ABS, PLA, PET G can be used for the screw extrusion process. The process comprises a single, helical-grooved extruder screw for pushing out the polymeric material out of a nozzle/orifice attached. The primal element is the extruder screw, the geometry of which decides the output rate and metering conditions. External heaters are provided to generate the necessary heat flux to melt the incoming thermoplastics. The heat flux sets the temperature profile, which determines various temperature-dependent properties such as viscosity. Viscosity is a measure of flow resistance and has an inverse relationship with
temperature. Other process parameters, such as screw speed and die geometry, also affect the extrusion velocity, output rate, productivity, torque, and power requirement.

### 1.1 Components & Parts

The screw extrusion process consists of various components and parts, primarily a single screw extruder, barrel, nozzle, breaker plate, hopper, heating unit, cooling jacket, and power drive.

An extruder screw is a solid metallic body with external helical grooves on it. These grooves are formed between two adjacent flights, along which the polymer flows. An extruder screw has three basic zones—feeding, heating (transition), and metering. Feeding is the starting zone near the hopper and is characterized by a gradually increasing root diameter. The feeding zone is followed by the melting zone, where an external heat source is present for melting and phase change of the incoming material. This region is characterized by a transition from gradually increasing to a reasonably constant root diameter. The final is the metering zone with the maximum constant root diameter throughout the area. It helps in proper metering and channelling the flow. The flow is entirely liquid in this region. The geometrical representation of a single screw extruder is shown in figure 2.

![Fig. 2 The geometry of a single screw extruder.](image)

The flight pitch \( p \) is the most critical design parameter that governs the polymer-melt flow and metering characteristics. It is defined in terms of the helix angle of the screw \( \phi \) and the screw diameter \( D \).

$$
\tan (\phi) = \frac{p}{\pi D}
$$

(1)

Based on the flight pitch, the extruder screw can be classified into various categories. The screw can have a constant helix angle throughout or a variable pitch. The variation in pitch can be in either incremental fashion or continuous fashion.

The barrel is a hollow cylindrical body that coaxially houses the extruder screw. It helps in pressure development for the material flow. Attached at the end of the barrel is the nozzle that converges the melt flow. The nozzle diameter determines the size of the extrudate. Typically, the circular nozzle size can be as large as 1 mm in diameter. Placed coaxially between the barrel and the nozzle, the breaker plate is used to homogenize and
straighten the flow. It contains a large number of countersunk holes, which allows melt flow without developing
death spots. A hopper-based feeding system is commonly used for screw extrusion applications. The hopper
design should be aesthetic and appealing, with optimum storage capacity and incoherence to the geometrical and
space constraints.

Heating is an inevitable step in the screw extrusion processing of thermoplastics. Multiple heaters are placed
over the barrel to provide gradual melting to achieve the required thermal gradient, which lowers the risk of
overheating, thereby avoiding the polymer's degradation. Shaped like an annular disc, cooling jackets with water
flow provide adequate cooling of granules. It helps in the unrestricted flow of granules through the screw extruder

A low RPM (Revolutions Per Minute), high torque, the motor-drive system is required for the screw extrusion
process. The power drive's primary function is to maintain a constant rotation of the extruder screw throughout
the process. Fluctuations in the screw rotation will cause changes in the extrudate dimensions. Thus, the
constancy of speed is an essential requirement of an extruder drive.

1.2 Mechanism

The primary mechanism of single-screw extrusion comprises solids conveying, melting or plasticization, and
melt pumping.

As seen in figure 3, the solid polymer from the hopper is fed to the extruder, which conveys it further. As the
polymer is fed forward, it is compacted by the solid conveying frictional forces.

The rubbing action generates heat, which, combined with the heaters' energy, raises the barrel surface and
develops a thin film pumped towards the metering section.

In the transition section, the screw conveys solids, melt the polymer, and pump the melt forward. At the end of
the transition unit, the solid should be converted entirely to a melt. The metering section creates a circulating
flow by scraping the melt from the barrel and forcing it down to the bottom of the screw flight.
The single-screw extruder’s metering section functions as a pump to move molten polymer out of the screw. The polymer is found to have an intricate flow pattern due to the drag and pressure-flow combination. It is customary to combine the actions of drag flow and pressure components in the melt-flow analysis.

1.3 Process Parameters

For a single screw extruder, the main process parameters that define the flow are screw geometry, melt temperature profile, and screw rotational speed. These process parameters also help in determining properties like torque requirement and power consumption.

Screw Geometry

Screw geometry, in terms of the pitch and its distribution along the length, is essential for determining the flow rate, metering, torque capacity, and power requirement.

An extruder screw with a diameter \((D)\) of 16 mm and \((L/D)\) ratio of 20 is designed. The overall length of the screw is divided into three zones. Each zone's size ratio in terms of screw diameter is set as feeding: melting: metering::10D: 6D: 4D.

The flights are of triangular sections with a minimum height of 0.5 mm. The root diameter in the feeding zone, increasing linearly, from 10 mm to 15 mm. This linear increase provides the initial compaction.

Based on pitch distribution, three different screw geometries are designed and analyzed.

1. Constant Pitch (CP)

A constant pitch (square pitch) screw with a pitch numerically equal to the screw diameter \((p=D)\) is designed with a helix angle \((\phi)\) of 17.65° from the screw axis.

2. Discrete Pitch (DP)

This geometry has three different pitch zones, which are incrementally varying. The pitch is constant in a particular zone and is 16 mm in the feeding zone, 8 mm in the melting zone, and 5 mm in the metering zone. The corresponding helix angles are 17.65°, 9.04°, and 5.68° respectively. The number of flight revolutions can be approximated using, \(L_s=p_s n_s\) where \(L_s\) is section length, \(p_s\) is section pitch, and \(n_s\) is the number of flight revolutions.

3. Variable Pitch (VP)

The pitch is varying, in a continuous fashion, after every flight revolution. The starting and the ending values of the pitch are kept the same as that of the discrete pitch screw geometry. The pitch variation is a geometric progression with a common ratio \((r)\). As the pitch is varied per revolution, the overall length of the screw will be the linear combination of all the pitches together. Mathematically,
16 + 16r + 16r^2 + 16r^3 + \cdots + 16r^{n-1} = 320 \tag{2}

where \( n \) is the total number of terms. Also,

\[ 16r^{n-1} = 5 \tag{3} \]

Solving the above two equations will yield \( r = 0.965 \) and \( n = 34 \).

---

**Fig. 4** Screw geometries, (a) Constant Pitch, (b) Discrete Pitch, and (c) Variable Pitch.

*Temperature Distribution*
A linear temperature profile along the screw length is taken as a process variable. Three different temperature profiles are selected, starting from the Glass-Transition-Temperature (GTT) of the thermoplastic up to three different final values of 230 °C, 260 °C 290 °C, respectively. GTT is the temperature at which the melt changes from a rigid "glassy" state into a rubbery-viscous state. The lower temperature limit is set at the beginning of the metering zone, while the upper limit reaches near the metering zone's end. As the temperature is beyond the GTT range, only the superheating is considered for power and heat flux calculations.

**Screw Speed**

The screw rotation (RPM) directly affects the polymer-melt flow. The higher the screw rotation, the more the flow rate. Although, for better metering, it should be as minimum as possible. The conflict between productivity, and precision, leads to an optimization problem, and the melt flow is often compromised between the two.

Screw rotation also affects the heating characteristics of the melt flow. The temperature profile is susceptible to screw speed. An optimal value for screw speed has to be set. Lower RPM will reduce the output rate and productivity, while higher RPM will cause inefficient burning.

In this research, the screw speed for every combination of screw geometry and temperature profile is varied from 15 RPM to 90 RPM in increments of 15 RPM.

The extruder screw and barrel are modelled as EN41B nitriding steel because of the "plastic-friendly" nature. The nozzle diameter is set to 1mm.

**2. Rheological Flow Analysis**

For this research, ABS thermoplastic is studied and characterized. Acrylonitrile Butadiene Styrene (ABS) is a common thermoplastic polymer used extensively in polymer processing and fabrication applications. It has a GTT of 105 °C and a heat capacity of 2345 J/kg-K[8]. The length over which the temperature profile is set is divided into three parts. The thermal power and average heat flux are calculated as given in the table below.

| Temperature Range | Starting Power (W) | Middle Power (W) | End Power (W) | Average Heat Flux (kW/m²) |
|-------------------|-------------------|------------------|---------------|--------------------------|
| 105 °C -230 °C    | 20.32458          | 15.40222         | 13.12736      | 1.822                    |
| 105 °C -260 °C    | 25.20218          | 19.09853         | 16.27845      | 2.259                    |
| 105 °C -290 °C    | 30.07978          | 22.79484         | 19.42955      | 2.697                    |

From the power values, it can be seen that the maximum power requirement is at the start to reach the required liquidity of the melt. After that, the power is required only to sustain the temperature range.

Rheological properties characterize the melt flow. An essential rheological property of a melt-flow is its viscosity, which is a measure of flow resistance. A highly viscous fluid is difficult to flow but easy to control and vice-versa.
ABS is a high viscosity polymer, modelled using the WLF model. William-Landel-Ferry or WLF model is an empirical equation associated with time-temperature superposition.

\[
\eta = \frac{\eta_0}{1 + \left(\frac{\eta_0 \dot{\gamma}}{\zeta^*}\right)^{1-n}}
\]  
(4.1)

\[
\eta_0 = D_1 \exp \left[-\frac{A_1 (T - T_a)}{A_2 + (T - T_a)}\right]
\]  
(4.2)

where \((\eta_0)\) is the zero-shear viscosity, \((\dot{\gamma})\) is the shear rate and \((T_a)\) is the GTT of ABS plastic. \(\zeta^*, n, D_1, A_1, A_2\) are other material-dependent constants.

The values of the WLF viscosity model parameters used in this study are \(n = 0.33, \zeta^* = 29 \text{ kPa}, D_1 = 3.631 \times 10^{11} \text{ Pa-s}, T_a = \text{GTT} = 378 \text{ K}, A_1 = 27.21 \) and \(A_2 = 92.85 \text{ K}[8]\).

The WLF model-based viscosity profile is curve fitted into a sixth-order polynomial, w.r.t. the absolute temperature (K) for computational simplicity.

\[
\eta = 10^{-7} T^6 - 0.0004 T^5 + 0.5013 T^4 - 326.92 T^3 + 119561 T^2 - 2 \times 10^7 T + 2 \times 10^9
\]  
(5)

The path lines traced by the polymer material are spiral, followed by the volume change down the extruder length. The helical volume can be assumed to be a solid sweep made by a rectangular section with height as the flight height \((H)\) and width as the minimum inter-flight distance \((W)\). When unwrapped, this helical polymer-melt volume will form a cuboidal strip, as shown in figure 5.
To calculate the flow-related properties, the following assumptions are made:

- The flow is a steady-state Newtonian flow.
- The channel width ($W$) is much greater than the channel depth/flight height ($H$).
- There is no leakage through the clearance.
- In the metering zone, the polymer melt is entirely liquid.

Based on these assumptions, a polymer-melt flow model is theorized[9]. The screw-rotation-driven drag flow represented the forward motion, and in the opposite direction is the back pressure-driven flow. The effects of screw rotation, screw design, and polymer melt-rheology are considered in this model.

The peripheral velocity ($v_r$) of the polymer-melt flow, due to the screw rotational velocity, $N$ (rotations per second), is in a plane perpendicular to the axis of the screw. The channel velocity ($v_z$) is inclined to the peripheral velocity at the helix angle.

$$v_r = \pi D N \quad v_z = v_r \cos \phi \quad (6)$$

Assuming a linear velocity gradient, though the channel height, the volumetric drag flow rate ($Q_d$) is given by:

$$Q_d = \bar{v}_z \cdot (\text{channel area}) = \frac{1}{2} v_z W H \quad (7)$$

where ($\bar{v}_z$) is the average channel velocity. Also,

$$W = p \cos \phi = \pi D \tan \phi \cos \phi = \pi D \sin \phi \quad (8)$$

Therefore, the drag based volume flow rate becomes,
\[ Q_d = \frac{1}{4} \pi^2.D^2.H.N. \sin 2\theta \] (9)

It can be seen that the screw profile had a direct implication on the drag flow. A larger helix angle generates higher drag flow. For better control and precise flow, lower values of pitch are needed. Going by an average approach, the average helix angle in the metering zone for the constant pitch, discrete pitch, and variable pitch is 17.65°, 5.68°, and 6.705°, respectively.

Pressure builds down the helical channel’s length due to the constriction from the nozzle. The pressure at the end of the channel is greater than the initial pressure, and this pressure-driven flow drives the polymer back towards the hopper. For this analysis, the flow between two parallel surfaces is assumed.

The velocity profile is parabolic. The expressions for average velocity (\(u_{\text{avg}}\)), maximum velocity (\(u_{\text{max}}\)), and pressured riven volumetric flow rate (\(Q_p\)) are given below:

\[ u_{\text{avg}} = \frac{\Delta P.H^2}{12. \mu.L_c} \] (10.1)

\[ u_{\text{max}} = \frac{\Delta P.H^2}{8. \mu.L_c} \] (10.2)

\[ Q_p = \frac{\Delta P.H^3.W}{12. \mu.L_c} \] (10.3)

\((\Delta P)\) is the pressure difference through the channel, and \((\mu)\) is the coefficient of viscosity. \((L_c)\) is overall channel length, and \((L_m)\) is metering zone length measured along the screw.

\[ L_c = \frac{L_m}{\sin \emptyset} \] (11)

The total volumetric flow is the algebraic sum of the drag and pressure-driven flow[10].

\[ Q = Q_d + Q_p = \frac{1}{4} \pi^2.D^2.H.N. \sin 2\emptyset - \frac{\Delta P.H^3.W}{12. \mu.L_c} \] (12)

The negative sign before the pressure-flow component indicates that the pressure drives the flow in the opposite direction. Using the continuity principle, the above equation can be equated to the nozzle’s outflow, which can be used to calculate \((\Delta P)\). The extruder screw has to generate enough torque to overcome \((\Delta P)\) to extruder out the material. The extrusion force along the flight channel will be the pressure times channel cross-sectional area.
The horizontal component of the force will provide the required torque. The ratio of total torque to the metering zone torque will be proportional to the total screw length and the metering zone length. The absolute torque requirement ($\tau$) and the power rating ($P$) can then be calculated as:

$$\tau = \frac{6. \mu. D. L}{H^2 \tan \phi} \left( \frac{\pi^2 \cdot D^2 \cdot H \cdot N \cdot \sin 2\phi}{4} - \frac{\pi \cdot d_N^2 \cdot v_N}{4} \right)$$  \hspace{1cm} (13.1)$$

$$P = \tau \cdot \omega$$  \hspace{1cm} (13.2)$$

where, $(d_N)$ is the nozzle diameter (1 mm) and $(v_N)$ is the extrusion velocity.

The mass flow rate is an important parameter that helps to analyze the output. The power consumption, due to screw rotation, also characterizes the process. Together, a new unit called the Sensitivity ($S$), defined as the ratio of mass flow rate generated per unit power, gives the process's complete effectiveness.

$$S \left( \frac{g}{kW \cdot hr} \right) = \frac{\text{mass flow rate} \left( \frac{g}{min} \right) \times 60 \left( \frac{min}{hr} \right)}{\text{Power} \ (kW)}$$  \hspace{1cm} (14)$$

Numerical analysis-assisted CFD simulations are done for design validation and optimization. For polymer-melt flow-based processes, the simulation should handle various aspects of the process such as time-temperature-based rheological behaviour, thermal distribution along with the melt flow, complex geometries, and curvatures, etc.[11] . Understanding the interrelationships between such parameters will lead to design development and
quality control standards[12]. Commercial CFD package, ANSYS Fluent, is used in this study. The analytical model used in this research is the $k$-$\omega$-SST (shear stress transport) model. $k$-$\omega$-SST is a robust model that uses two equations based on viscosity-assisted eddy flow-based turbulence. It is associated with the Reynolds-averaged Navier-Stokes (RANS) family of turbulence models. The two variables calculated, $k$ and $\omega$, denote the turbulence kinetic energy and dissipation rate of the eddies, respectively.

The governing equations of the $k$-$\omega$-SST model are [13]:

\[
\frac{Dpk}{Dt} = \tau_{ij} \frac{\partial u_i}{\partial x_j} - \beta^* \rho \omega k + \frac{\partial}{\partial x_j} \left[ \left( \mu + \sigma_k \mu_t \right) \frac{\partial k}{\partial x_j} \right] \tag{15.1}
\]

\[
\frac{D\rho \omega}{Dt} = \frac{\nu_t}{v_t} \tau_{ij} \frac{\partial u_i}{\partial x_j} - \beta \rho \omega^2 + \frac{\partial}{\partial x_j} \left[ \left( \mu + \sigma_\omega \mu_t \right) \frac{\partial \omega}{\partial x_j} \right] + 2(1 - F_1) \rho \sigma_\omega \frac{1}{\omega} \frac{\partial k}{\partial x_j} \frac{\partial \omega}{\partial x_j} \tag{15.2}
\]

where $D/Dt = \partial / \partial t + u_i \partial / \partial x_i$; $\sigma_k$ and $\sigma_\omega$ are the closure coefficients for $k$ and $\omega$, respectively and $\mu$ and $\mu_t$ denotes the molecular and eddy viscosity[14]. $(1-F_1)$ The blending function is used to gradually transition from the standard $k$-$\omega$ model near the walls to a high Reynolds number flow, characterized by the $k$-$\varepsilon$ model in the boundary layer's outer portions.

\[
F_1 = \tanh(arg_1^T) \tag{16.1}
\]

\[
arg_1 = \min \left[ \max \left( \frac{\sqrt{k}}{0.9 \omega y}, \frac{500v}{y^2 \omega} \right), \frac{4 \rho \sigma_\omega k}{CD_{k\omega} y^2} \right] \tag{16.2}
\]

\[
CD_{k\omega} = \max \left( 2 \rho \sigma_\omega \frac{1}{\omega} \frac{\partial k}{\partial x_j} \frac{\partial \omega}{\partial x_j} ; 10^{-20} \right) \tag{16.3}
\]

$y$ is the distance of the following surface and $CD_{k\omega}$ is the non-negative portion of the cross-diffusion term.

The CAD models of the screw extruder assemblies are made in SOLIDWORKS 2019. The assembly models are saved in (.iges) format and are edited in the ANSYS design modeler (DM) for fluid volume extraction. The portion beyond the metering zone is considered for fluid volume. Meshing is done at 0.55 mm element size (figure 7 (a)) for all the screw geometries. The patch conforming meshing method is used to discretize the computational domain into tetrahedral and wedge elements. A total of 210772 nodes and 599063 elements are created. Orthogonal quality is checked for all mesh metrics, as shown in figure 7 (b).
Tet4 and Wed6 represent the 4-node linear tetrahedral and 6-node linear wedge elements, respectively. It is observed that element metric with 0.88 orthogonal quality has the maximum number of elements. Most of the elements are lying beyond 0.5 element metrics, implying the mesh's stability and "goodness". The mesh is transferred to ANSYS Fluent, where every simulation is run for 1000 iterations. Each iteration is monitored based on the residues (percentage error) in $k$, $\omega$, energy, continuity, and velocity components. The iterations are complete once a convergence of less than 0.001% is achieved.

Steel is selected as the solid material for screw and barrel material with density, 8030 kg/m$^3$, specific heat, 502.48 J/kg-K, and thermal conductivity, 16.27 W/m-K. Fluid material is set as ABS with density, specific heat, and thermal conductivity as 940 kg/m$^3$, 2345 J/kg-K, and 0.18 W/m-K[8].

Results and Discussions

Effect of process variables
There is a linear correlation between the theoretically calculated and computationally simulated extrusion velocities for all values. It is also found that there is an overlap of extrusion velocities for a given screw geometry and screw speed for different values of heat flux.

![Fig. 8 Theoretical vs computed extrusion velocities.](chart)

With an increase in RPM, the extrusion velocity increases for a given screw geometry and heat flux. With an increase in the helix angle, the extrusion velocity increases for a given RPM and heat flux. As seen from the standard deviation values (table 2), the given heat fluxes do not affect the output rate. It can be inferred from the viscosity distribution that the viscosity converges for the given temperature distributions, thereby offering a constant resistance. It is also found that with an increase in RPM, the extrudate temperature decreases for a given heat flux. As the screw speed increases, the interaction time between the heated wall and polymer decreases. Hence, with an increase in RPM, the heat flux should also increase for proper melting and polymer grains fusion.

**Table 2** Mean and standard deviation (SD) of mass flow rates (g/min) for various process variables

| Process Variable | 1.8 kW/m² | 2.26 kW/m² | 2.69 kW/m² | Mean         | SD           |
|------------------|-----------|------------|------------|--------------|--------------|
| RPM 15           | 2.956812658 | 2.961506942 | 2.961722512 | 2.960014038  | 0.00277457   |
| RPM 30           | 5.924499631 | 5.923994022 | 5.924162854 | 5.924162854  | 0.000291658  |
| RPM 45           | 8.88564852  | 8.885658978 | 8.885658978 | 8.8856586105 | 0.000201024  |
| RPM 60           | 11.84749262 | 11.84812087 | 11.84763872 | 11.84763872  | 0.000428212  |
| RPM 75           | 14.80942366 | 14.80915802 | 14.80964769 | 14.80964769  | 0.00063219   |
| RPM 90           | 17.7712697  | 17.77067333 | 17.77124712 | 17.77106338  | 0.000337985  |
| CP               |           |            |            |              |              |
The DP screw provides the best metering characteristics for polymer-melt extrusion. For a given RPM and heat flux, the DP screw provides the best velocity control and resolution. An extruder screw’s output can be increased by increasing the RPM, but the screw geometry characterizes the output resolution. In DP, the incremental decrease in the pitch helps in the grain compaction and heat transfer, thereby providing enhanced melting. The final decrease in the pitch from melting to the metering zone provides better control. Decreasing the pitch further may prohibit the polymer flow and cause a blockage. Lowering the pitch also increases the back pressure and torque requirement. A pressure drop of 430 MPa is calculated in the DP screw's metering zone. The calculated torque and power requirements for the DP screw are 4.3 Nm and 6.75 W. The corresponding screw sensitivity is 26.252 kg/kW-hr and the associated volume flow rate observed is 52.43 mm$^3$/s. Going by conventional thermoplastics 3D printing using FDM, SEAM delivers 7-12 folds output. Comminal et al. reported a volume flow rate of 7.55 mm$^3$/s using a 0.4 mm nozzle and 60 mm/s deposition speed[15]. Coogan et al. reported a volume flow rate of 4.33 mm$^3$/s at 0.1 mm layer height, 0.65 mm road width, and 4000 mm/min traverse speed[16].

Strain rate and pressure drop in the nozzle are also calculated in the nozzle tip, using the Hagen-Poiseuille equations:

$$\Delta P = \frac{8 \eta P L}{r^4} \quad \dot{\gamma} = \frac{4v}{r} \quad (17)$$

For a tip length and radius of 11.53 mm and 0.5 mm, the maximum calculated pressure drop is $2.49 \times 10^8$ kg/cm$^2$, observed in VP screw at 90 RPM and 1.8 kW/m$^2$ heat flux. The nozzle pressure drop can be as high as $6.74 \times 10^8$ kg/cm$^2$ [17]. The maximum calculated nozzle strain rate is ~6465 s$^{-1}$, observed in constant pitch screw at 90 RPM and 1.8 kW/m$^2$ heat flux.

SEAM is a versatile material extrusion technique for 3D printing applications. The use of polymer grains as the starting raw material adds to the material flexibility and cost reduction. The extruder screw is the heart of the process. The flight geometry determines the metering characteristics, output flow rate, and power requirement of
the extruder screw. The upper-temperature limit beyond 230°C causes saturation in viscosity value and does not significantly affect the output. Screw speed has a direct implication on productivity. A discrete pitch screw design with incrementally varying helix angle provides the best metering characteristics because of its minimum pitch in the metering zone. The discrete pitch screw presented has a power requirement and sensitivity of 6.75 W and 26.252 kg/kWhr, respectively. In terms of volume flow rate, SEAM's productivity is 7-12 times higher than typical FDM 3D printing. However, every screw design is a compromise between melt temperature, productivity, and power requirement.

Declarations

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Conflict of Interest

The authors declare no conflict of interest.

Data availability

The raw data used in this work can be made available upon request

Code of availability

Not applicable.

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Figures

Figure 1

Types of MEAM (a) Pinch rollers based, (b) Piston based, and (c) Screw extrusion based.

Figure 2

The geometry of a single screw extruder.

Figure 3

Cross-section through a screw extruder.
Figure 4

Screw geometries, (a) Constant Pitch, (b) Discrete Pitch, and (c) Variable Pitch.
Figure 5

(a) Geometry features of the extruder screw, (b) schematic of the unwrapped material.

Figure 6

Schematic of the pressure force and torque balance.
Figure 7

(a) Mesh profile, and (b) orthogonal quality of various mesh elements.

Figure 8

Theoretical vs computed extrusion velocities.