Proc. of the 9th Intl. Conf. of Asian Society for Precision Engg. and Nanotechnology (ASPEN 2022)
15–18 November 2022, Singapore. Edited by Nai Mui Ling Sharon and A. Senthil Kumar
doi://10.3850/978-981-18-6021-8_OR-01-0036

Fin Design for Passive Cooling in Screw Extrusion Additive Manufacturing (SEAM)

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KEYWORDS: Additive Manufacturing (AM), Single Screw Extrusion, Passive Cooling, Fin Design, Heat Transfer Simulation

Additive manufacturing (AM), also called 3D printing (3DP), is a state-of-the-art, non-conventional manufacturing process, that enables solid physical realization of a given CAD (computer-aided-design) model, via layer-by-layer deposition. Over the years, various AM techniques have been developed, for various choices of feed materials and forms. Thermoplastics are one of the most commonly used material choices for AM applications which are 3D printed using the technique of fused deposition modeling (FDM) or fused filament fabrication (FFF). FDM is based on pinch-wheel extrusion where the thermoplastic material in filament/wire form, is pinch fed into a liquefier. The material is melted, continuously extruded, and selectively deposited over the built platform, to get the desired geometry. Although being one of the most widely used AM techniques, FDM suffers from various bottlenecks such as low part strength, high material cost, huge printing time, poor surface finish, and non-conformal slicing, which limit its usage for prototyping purposes only. Screw extrusion-based additive manufacturing (SEAM) is a material-extrusion technique that also employs continuous extrusion and selective deposition via a single-screw extruder. It is commonly applied for thermoplastic materials in granular form and is hence, also called fused granular fabrication (FGF). The use of granular feed form, instead of the typical wire, reduces the material cost by almost 90 % and manufacturing cost by almost 50 %. Screw extrusion also provides escalated outputs and flow metering, which helps in reducing the overall printing time. The liquefier region in SEAM is much larger than FDM, thus providing better heating conditions, which has a direct consequence on the part strength. Because of the before mentioned reasons, SEAM is explored as an alternative for FDM. SEAM set-ups typically have a liquefier zone, for melting and phase change of the thermoplastic material; and a cooling zone, which is placed near the throat area. Granular material feeding happens at the throat area and should be maintained well below the softening point of the thermoplastic material to avoid blockage and choking of the set-up. Active cooling devices such as water jackets and cooling fans are commonly employed but add up to the cost and additional maintenance. In this research, passive cooling devices such as fins, are designed, developed, and fabricated for a single screw extrusion-based additive manufacturing set-up for 3D printing applications using thermoplastic ABS (Acrylonitrile Butadiene Styrene) material. Circular-shaped fins are designed for aluminum, considering the availability and ease of manufacturability. Iterations are made for the number of fins required with limiting conditions on the peak temperature near the throat area, for a given liquefier temperature. Steady-state heat transfer simulations are carried out using the thermal simulations module on SolidWorks2021. The final design is then fabricated and tested on a SEAM set-up. The current design presents a fin-based passive cooling approach for SEAM set-up and doesn't require any additional assembly or control.

1. Introduction

Additive Manufacturing (*AM*), commonly termed as 3D Printing (*3DP*) is a novel technique for converting a 3D model into a physical form, via layer-by-layer realization. First conceptualized in the 1980s, *AM* has been developed into various types for different applications and materials [1]. Out of the many techniques, Material Extrusion based AM, i.e., *MEAM*, is very common, in which the technique of Fused Deposition Modeling (*FDM*) is the most widely used. While *FDM* used polymeric material in filament form, another *MEAM* technique of screw extrusion (*SEAM*) is based on granular feedstock which gives more material flexibility and reduces the overall printing cost. Thermoplastic pellets are hopper fed into the screw extruder assembly via the throat at the feeding zone. The screw rotation pushes the granules further down, along the length of the extruder, into the heating zone, where they are melted in the presence of the external heaters (usually contact-based resistive heaters). The melted polymer is pushed further down into the metering zone, for final compaction and densification. The material is then extruded out of the nozzle at the end of the barrel. The screw extruder assembly coupled with a motion system, enables selective deposition, forming the *SEAM* set-up. *SEAM* also provides higher deposition rates than *FDM* [2].

Heating & cooling are inevitable steps in any *MEAM* technique. While heating is required for necessary phase changes for extrusion, cooling is required for heat entrapment below the throat area. Conventional *SEAM* set-ups use water-cooled jackets, which are although simple to install but have various issues related to maintenance, leakage, flow & temperature control and availability of water source.

In this research, inspired by the fin-based heat dissipation systems, a fin-based passive cooling device is presented. The design is computationally validated and physically implemented over a given *SEAM* set-up.

2. Materials & Methods

2.1 Experimental Set-up

A single-screw extruder set-up is fabricated along with all the associated parts. The conventional extruder screws have three discrete zones which help in the pressure development but also load up the drive motor [3]. Additionally, the screw extruder for *AM* purposes needs to be repeatedly started and stopped which can generate a lot of stress on the drive motor. Therefore, a single flight, high pitch screw design is chosen, especially for *SEAM*, keeping in mind, that the primary function of the screw is to feed the polymer pellets into the heating zone and extruder the melt through the nozzle. The torque requirement and the generated stress are heavily reduced with this approach. A similar technique is also employed by Whyman et al. for the *3D printing* of biopolymer pellets [4].

The screw and barrel are made of EN41B alloy steel. A bronze nozzle with a 1 mm diameter is attached to the barrel's end. Thermoplastic *ABS* in pelletized form is hopper fed into the system. A *PID*-controlled, resistive-based band heater is placed circumferentially onto the barrel. A high torque stepper motor is used to drive the extruder screw. Combining the extruder assembly with a 3-axis *CNC* forms the given *SEAM* set-up, as shown in Fig. 1.

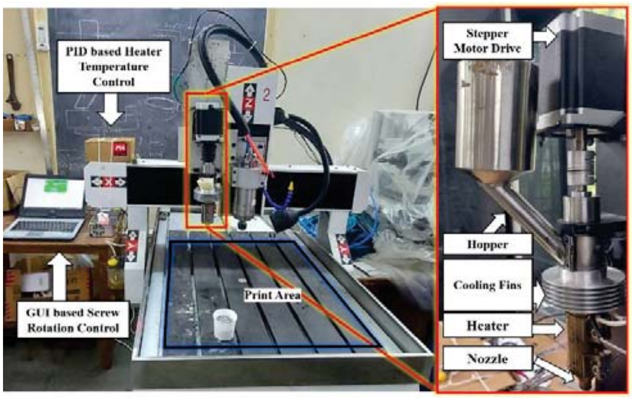


Fig. 1 The indigenously fabricated SEAM experimental set-up

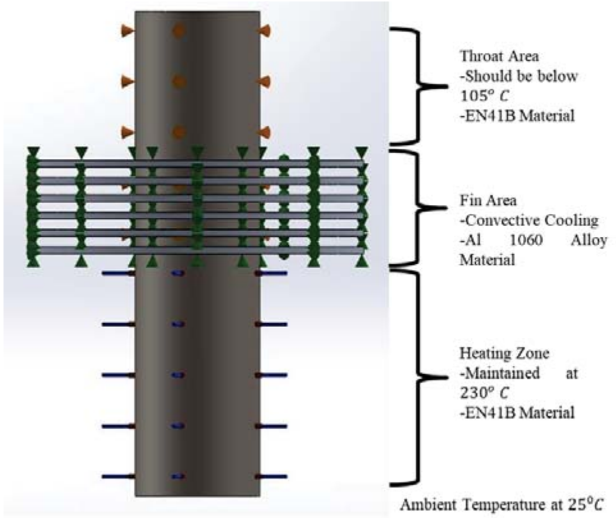


Fig. 2 Schematics of the arrangement for simulations.

2.1.1 Computational Simulations and Fabrication

Because of the cylindrical nature of screw extruder set-up, annular fin design is chosen, as they are axis-symmetric. The size of the fins, in terms of inner and outer diameter (*d* & *D*), are dictated by the barrel size (36 mm) and the space constraints. The minimum features of fin thickness (*t*) and spacing (*s*) are determined by the machinability of the fin material. In this analysis Aluminium (1060 Alloy) is used as the preferred material of choice, because of its superior thermal properties. The number of fins is to be determined such that the entrapped heat does not raise the temperature at the throat area (T_t) above the glass transition temperature (*GTT*) of the polymeric material (*ABS* here).

ABS is a commonly used thermoplastic material for *AM* applications [5]. It has a *GTT* of about 105^0C, below which it remains hard and glass but begins to flow beyond that. The condition is to keep the throat temperature below the *GTT*, i.e., $T_t < GTT$, so that the polymeric material does not melt and choke the extruder. The given arrangement is a complex heat transfer problem where the fin arrangement should be such that the required heat dissipation should keep the temperature above the fins less than the *GTT* while the bottom of the fins is maintained at the extrusion temperature, 230^0C for ABS [6]. The total fin area, which is majorly dictated by the number of fins is determined via computational heat transfer simulations using the thermal module in *SolidWorks2021*.

Three regions are considered for the heat transfer simulations: the heating zone, fin area and throat area, as shown in Fig 2. The heating zone is given a constant temperature of 230^0C, while the fin and throat area are given a convective load. The number of fins is incrementally increased and the temperature profile is analyzed for each case until the throat temperature is significantly below the *GTT*.

The various properties and parameters used in the simulations are mentioned in Table 1 and the results (temperature profiles) are shown in Fig. 3.

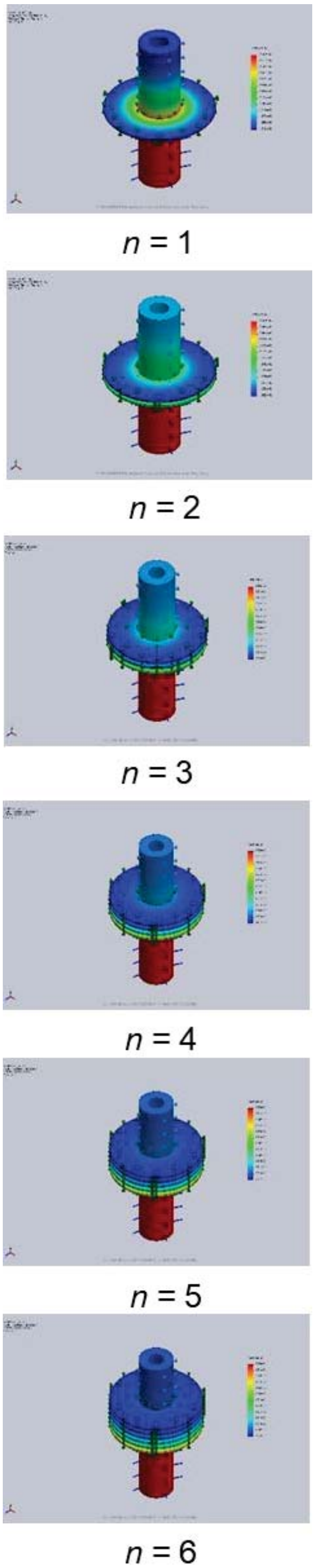


Fig. 3 Heat transfer simulation results of temperature profiles for various fin numbers, generated using *SolidWorks2021*.

Table 1 Parameters used in the simulation

Property	Value
Fin features: *d, D, t, s*	56, 96, 2, 3 (all in mm)
Convection coefficient for Aluminum Fins	60 W/m^2K [7]
Convection coefficient for EN41B Alloy Steel Barrel	25 W/m^2K [8]
Normal air velocity	3 m/s
Mesh Type	Solid
Average Element Size	5.02532 mm
Total Nodes & Elements	30676 & 16281
Maximum Aspect Ratio	7.21
% of Elements with Aspect Ratio < 3	87

The throat temperature is plotted against various fin numbers in Fig. 4 and it is observed that a threshold is achieved when the number of fins is between 4 & 5. For the safer side, six fins are considered. The final geometry is fabricated and installed over the screw extruder set-up. The cooling capacity of the fin-based passive cooling is also compared with the conventional water-cooling jacket (Fig. 5). The effect of various cooling units in terms of throat area temperature, is mentioned in Table 2.

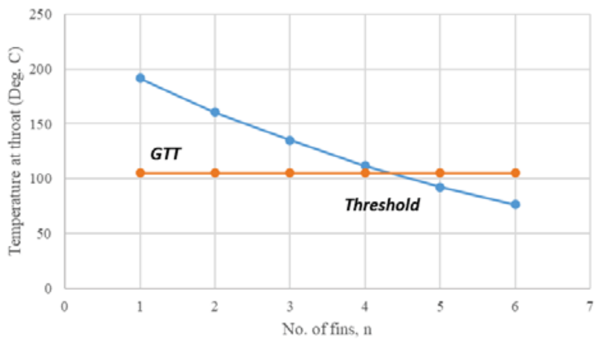


Fig. 4 Effect of variation of number of fins on the throat temperature

Table 2 Effect of various cooling units on the throat temperature

Condition	Value (^0C)
Without any cooling unit	135±14
With water-cooled jacket	65±7
With cooling fins	80±10

3. Conclusions

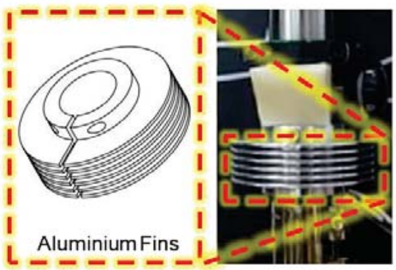
Heating, as well as colling, are crucial processes in *SEAM.* The heating is required to melt the thermoplastic material for extrusion while the cooling is required to trap the heat in the required region only. Conventionally water-cooled jackets are placed between the heating unit(s) and the throat area of the extruder, to avoid choking the extruder. These water jackets have to be custom fabricated as per the extruder shape and rated output. These cooling measures also add up to their installation, maintenance and separate control. Hence, a fin-based passive cooling device is proposed in this research as an alternative to the cooling jackets. Inspired by the conventional *AM* technique of *FDM*, where fins with cooling fans, are used for heat entrapment, a similar approach is used for the *SEAM* set-up for extrusion of thermoplastic *ABS*.

Being axis-symmetric, an annular fin design is chosen to compliment the cylindrical geometry of the screw extruder. The fin size (inner and outer radius) is dictated by the barrel size and space constraints. The thickness and spacing of the fins are based on the choice of material and its machinability. Aluminum (1060 Alloy) is used for fin fabrication because of its superior thermal performance, ease of availability and machinability.

The required number of fins is computationally estimated via steady state heat transfer simulation, using *SolidWorks2021*. The peak temperature is set to the extrusion temperature of *ABS* (230^0C) and the ambient is set at 25^0C. The condition is set that the temperature at the throat area should be less than the glass transition point of the thermoplastic (105^0C for *ABS*). A threshold is achieved when the number of fins is 6.

For physical verification, the designed fin is fabricated out of aluminum and installed over the set-up. It is observed that the passive cooling using the aluminum fins is almost 80% efficient as that of the conventional water-based cooling jackets. The passive cooling system can provide simpler installation, easy control, low maintenance and low operational costs than the conventional water-cooling routes

(a)



(b)

Fig. 5 (a) Screw extruder set-up conventional water-cooling jacket (highlighted), (b) Aluminum fins for passive cooling, installed below the throat area

ACKNOWLEDGEMENT

The authors would like to acknowledge the significant and valuable contributions of Mr. Glen D'souza, especially for his assistance in the fabrication of the aluminum fins. Mr. Glen is currently a senior project staff at the Rapid Manufacturing (RM) Lab, Mechanical Engineering Department, Indian Institute of Technology (IIT) Bombay, Mumbai, India.

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