Extrudate Mass Flow Rate Analysis in Fused Filament Fabrication (FFF): A Cursory Investigation of the Effects of Printer Parameters

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Abstract

In the Fused Filament Fabrication (FFF) process, a nozzle deposits a polymer melt through an extrusion process to create the end-use part. Four significant parameters influence this process: the nozzle diameter, print speed, layer height and the nozzle temperature. The results suggest that these parameters must be all considered to ensure actual extrusion rates equal software specified values. As expected, the results indicated there is an ideal nozzle temperature range for each combination of the other three parameters. Surprisingly, this temperature window varies from as low as 180°C to over 250°C for the polylactic acid (PLA) resin that was tested. This suggests that the buildup of nozzle pressure varies widely due to the volumetric flow rate and nozzle temperature and must be accounted for if under extrusion is to be avoided both to improve quality and to remove this as a convoluting factor for other FFF research.

Introduction

The expiration of the initial patents held by Stratasys for the Fused Deposition Modeling (FDM) has led to an influx of prosumer open-source desktop printers, which retail for between $1,500 to $5,000, for example, the printers manufactured by Ultimaker, Lulzbot, Markergear, etc.[1, 2]. These systems have created a niche below the industrial units produced by Stratasys that cost more than $100,000. The FDM process, also known as Fused Filament Fabrication (FFF), has exploded into popular culture, especially after 3D printing was dubbed the Third Industrial Revolution by the world-renowned economist, Jeremy Rifkin in 2011[3].

Commonly known as the liquefier, the assembly responsible for melting the filament has a heated nozzle and is at the heart of the FFF process. For a successful print, the brass nozzle must sufficiently raise the temperature of the filament being fed into the liquefier at various rates [4–7]. One approach for investigating the non-Newtonian fluid dynamics and heat transfer occurring within the liquefier is through analytic models or simulations, such as finite elements [8]. These techniques have been used to suggest optimized nozzle geometries or ideal process parameters such as temperature, feed rate, etc. Interestingly, the assembly has been dubbed the liquefier even though the material being extruded is not a liquid but rather a polymer melt, which is a viscoelastic fluid that exhibits non-Newtonian behavior as shear thinning was observed by Koch[9].

The mass throughput affects both the cosmetic and mechanical properties. Pfeifer et al. and Koch showed that the strength of a Type 1 tensile bars can vary from 3 to almost 30 MPa when the solidity of the part was between 63 and 100% [9,10]. The importance of solidity also motivated the work of Qiu et al., which focused on optimization of the toolpath to eliminate voids[11], [12]. It is interesting to see scrutiny of voids when under-extrusion could undo the gains from toolpath optimization regarding mechanical properties.

Therefore, it appears to be prudent first to determine if a desktop FFF printer’s experimental and theoretical mass throughput as equal. When a deviation occurs, it is also important to identify the printer parameters responsible for the under extrusion. This work explores the effects of four print parameters on a Ultimaker 2+ equipped with three of the four standard nozzles (0.4, 0.6 and 0.8 mm in diameter). The parameters investigated were the nozzle temperature, theoretical print speed, theoretical layer height and the nozzle diameter.

Materials

All experiments were conducted with commercially available MatterHackers 3 mm Black PLA filament, lot number 2016-01-13. The actual diameter was 2.93 ± 0.07 mm[10]. The manufacturer reported density, $\rho$, was 1.25 g/cm$^3$.

Experimental

An Ultimaker 2+, S/N: UM9502A00MES133704-03, equipped with a 0.4, 0.6, or 0.8 mm OEM nozzle was used for all experiments[13]. All G-Code commands were input via the terminal in Cura Lulzbot 19. Extrudate mass was measured with an OHaus Explorer EX125 D, S/N: B505560918, analytic balance. All tests were completed in quadruplicate.

Protocol Development

As no standard exists for determining if a printer’s mass throughput is as expected for, it was first necessary to develop a protocol that is capable of capturing the effects of a parametric variation without being convoluted by
external factors. A series of decisions had to be made regarding how the mass throughput was to be measured.

First, should the extrusion be measured when material was deposited onto a built platform, onto an existing layer or into free volume? As a theoretical maximum deposition was to be measured, the influence of back pressure would only decrease this value, but more importantly bed-leveling issues or the unevenness of the previous layer would result in varied back pressure, which would introduce additional variables. Therefore, for this cursory exploration material was extruded with the nozzle raised a few centimeters above the build platform.

Second, a length of time for extrusion was set to 30 s. Compared to an actual print, 30 s is an abnormally long continuous extrusion. The primary justification for an extended period of extrusion was to mitigate the influence of non-steady-state extrusion, e.g. pressure build-up in the nozzle. Therefore, an extrusion time of 30, 60 and 120 s was explored. Ultimately, 30 seconds was used for the standard time.

The last and most difficult decision was to choose between starting the collection of the extrudate once extrusion reached steady-state or to input an extrusion 30, 60, 120 s and include the non-steady state extrusion as the onset and end. This involved the decision to include or disregard the material that exits the die after the filament movement is stopped but flow continues due to residual pressure in the nozzle. Since in the FFF process this residual pressure doesn’t represent any segment of proper printing, this material was not included. However, as there are instances where the nozzle has traveled significant distances and could have lost pressure two initial conditions were explored. First, when the nozzle pressure is essentially zero and second, when the nozzle pressure is already at steady-state.

Parameters

Four of the most significant parameters, nozzle diameter, print speed and layer height and nozzle temperature, were investigated to determine their effect on the extrudate mass flow rate, \( \dot{m} \). When selecting what range of the parameter to test, the values were determined through a combination of the Ultimaker 2+ specification sheet, which includes recommended parameters, the defaults in Cura 2.1, which was developed specifically for Ultimaker and personal experience.

For print speed, 25, 50 and 75 mm/s was selected. 50 mm/s is the default speed in Cura 2.1, 25 mm/s is the default for the outer perimeter and the initial layer speed[14]. The upper bound of 75 mm/s was arbitrary and selected as the linear step above 25 and 50 mm/s.

For layer height, Ultimaker recommends a maximum of 0.150, 0.200, 0.400 and 0.600 mm for a nozzle with a diameter of 0.25, 0.40, 0.60 and 0.80 mm, respectively. As the maximum suggested layer ranged from \( \frac{1}{2} \) to \( \frac{3}{4} \) of the nozzle diameter, layer heights of \( \frac{1}{4} \), \( \frac{1}{2} \) and \( \frac{3}{4} \) of the nozzle diameter were tested for each nozzle size. For the 0.6 mm nozzle, a 4\textsuperscript{th} layer height of 0.2 mm or a third of the nozzle diameter was added since both the 0.4 and 0.8 mm nozzles had a layer height of 0.2 mm, which afforded the opportunity for more comparisons.

The temperatures of interest were determined by the maximum nozzle temperature for the printer, 250°C and the minimum temperature were extrusion would still occur for a large nozzle diameter at the highest volumetric throughput. This value was 180°C, which coincidentally was the minimum bound set by the firmware. With a modified firmware to allow extrusion at lower temperatures, result suggested that at 170°C the filament could not generated sufficient pressure for extrusion at these high viscosities. Therefore, a temperature range of 180 to 250°C with 10°C steps was used.

In summary for each nozzle size, 8 temperatures, 3 print speeds, and 3 or 4 layer heights were explored. In addition, to a series of tests designed to test assumptions to validate the developed protocol.

Results

An early decision that needed to be made was whether \( \dot{m} \) should or should not include the non-steady-state period at the onset of a new period of extrusion. This is the period between the start of filament movement into the liquefier until the polymer melt begins to exit the nozzle at a constant rate, which varies based on the parameters of interest.

From the results in Figure 1, it can be seen that 30 seconds of steady state extrusion yields more extrudate. This is as expected as pressure must first be built up in the nozzle before extrusion since \( \dot{m} = \dot{m}(p) \) since the volumetric flow, \( Q \), through a tube is given by

\[
Q = \frac{\pi \Delta p}{8 \mu L} R^4 \quad \text{Eq. 1}
\]

where \( \Delta p \) is the pressure drop, \( \mu \) is the Newtonian viscosity, \( L \) is the length of the tube and \( R \) is the radius. In the case of FDM process, \( L \) and \( R \) would be dependent on the nozzle geometry. The result suggests that at lower viscosities (high temperatures) it takes longer for steady state pressure to be reached due to the larger mass deviation from steady state. Additionally, the results show that at lower flow rates (thinner layer height and slower print speed) the temperature at which the effects of this are noticeable is lower. This is can been around 230, 210 and 200°C for layer heights of 0.3, 0.2 and 0.15 mm, respectively.
Figure 1. A comparison 30 seconds of extrudate for the 0.6 mm nozzle for 4 theoretical layer heights (0.15 mm – gray, 0.20 mm – tan, 0.30 mm – burgundy and 0.45 mm – red) for a print speed of 25 mm/s. The solid line is steady state extrusion, and the dashed line includes the onset period during which nozzle pressure is increasing. The black dotted line represents the theoretical extrusion for each of the four layer heights.

Reassuringly, the steady-state $m$ matched the theoretical $m$ determined with

$$m = s \cdot h \cdot D \cdot \rho \quad \text{Eq. 2}$$

where $s$ is the print speed, $h$ is the layer height, $D$ is the nozzle diameter and $\rho$ is the density of the polymer. It should be noted that the density used was supplied by the filament manufacturer and that printing software, such as Cura, does not use a temperature dependent density, or differentiate between the solid versus melt density.

While the steady-state data may give a more accurate description of the majority of normal printer operation since periods between extrusion are short and nozzle pressure is maintained, the goal of this work was to investigate causes for under extrusion. Therefore, all subsequent results will not include steady-state extrusion.

The hypothesis that the difference from steady-state was due to the time required to build up pressure was reinforced with the results presented in Figure 2. Regardless of total extrusion time, the time for to pressure buildup would remain constant, and longer continuous extrusion would mitigate its effect. Since 30 s showed a larger deviation than 60 s and 120 s showed almost none, this hypothesis is further supported.

Figure 2. Comparison of extrusion for 30 (grey), 60 (tan) or 120 s (red) for the 0.8 mm nozzle at 25 mm/s for a 0.2 mm layer height. The result suggests that the significant under extrusion, up to 60%, at temperatures above 200°C can be attributed to the onset of extrusion as this period should remain constant but becomes a smaller percent of the total extrusion time.

Figure 3. A comparison of printing at 25 mm/s (grey), 50 mm/s (tan) and 75 mm/s (red) with the 0.4 mm nozzle for a layer height of 0.3 mm.
One final result was the difference between a brand new OEM nozzle and an OEM nozzle that had been used and clean per manufacturer recommendations. While the typical trend of under extrusion at high volumetric flow rates is still evident, it is noteworthy that the \( n \) was always greater for the new nozzle. Additional data would be required to determine the cause of this observation; however, it is important to recognize that the source of under extrusion could be due to a variety of reasons. The most plausible explanation here is the buildup of degraded polymer restricted the flow through the nozzle.

**Discussion**

There is one major conclusion that can be drawn from the results. Under extrusion occurs when the nozzle temperature is not appropriately selected for the given volumetric throughput. Either the flow rate is too high or too low for the given nozzle temperature. Therefore, it appears that for each flow rate an ideal temperature or temperature range exists, which yields the predicted extrudate mass.

Considering these data, it is interesting to find that manufacturers of FFF printers are aware of under extrusion but offer limited information about this issue and some of the advice might be misleading. For example, Ultimaker claims the danger of raising the temperature too high is an acceleration of degraded material buildup in the nozzle, which could result in clogs[15]. Nowhere is it mentioned that nozzle temperature selection should be based on throughput (print speed, layer height, nozzle diameter). If anything, users might shy away from using the proper temperatures since it is higher.

One example of under extrusion can be seen in Figure 1, where steady-state extrusion is compared with extrusion starting with no nozzle pressure. With a theoretical layer height of 0.15 and 0.2 mm and a print speed of 25 mm/s, this is representative of printing the first layer. However, due to the presumable difficulty with building nozzle pressure at these lower mass throughputs, steady-state extrusion yielded between two and four times as much material over 30 seconds at temperatures greater than 210°C, which is in the middle of recommended nozzle temperature and well within the recommendations of maximum layer height for the given nozzle. Interestingly, if the nozzle is cooled to less than 200°C, the difference is decreased to as little as 5% due to the onset of extrusion.

Decreasing temperature is never a rule of thumb in the FFF community but increasing the layer height for the first layer is a common recommendation seen on websites and forums. Figure 1 could explain this until now unsupported claim since for the layer heights of 0.3 mm the significant deviation began at 230°C and above 250°C for the 0.45 mm layer height. A possible explain is that the volumetric flow rate is maintained at this slower print speed by increasing the layer height. While increasing the first layer height to compensate for the slow print speed required for good bed adhesion is a bandage for this problem, the better solution may be to include the option to print the first
layer at a lower nozzle temperature. Alternatively, the printer could maintain a constant melt temperature regardless of print speed.

Switching to the other end of the spectrum, extrusion of thick layers, 0.45 mm, with the 0.6 mm nozzle at high print speeds (75 mm/s) the recommendation of print temperatures may once again not be suitable. The results shown in Figure 1 suggest that much higher nozzle temperatures are required.

As temperature is repeatedly included in discussion, it should be noted that the temperature of the extrudate was never explicitly measured but the results do suggest that it did not always reach the nozzle temperature. When looking at the 200°C nozzle temperature in Figures 1, 3 and 4, which are comparing various volumetric flow rates only some of the combinations of parameters yield under extrusion, which is as large as 25%. In addition, under extrusion always increases as the rate at which the filament is being fed into the liquefier is increased. If assumed that this increased feed rate decrease residence time in the liquefier a reasonable conclusion would be that the material warms less and since viscosity is a function of temperature, the viscosity is presumably higher. Modeling or simulation would be an excellent method to support this hypothesis and to help predict melting behavior for a wide range of resins.

Even though these results indicate caution must be taken when selecting print parameters, Figure 2 show promise for FFF, especially when steady-state extrusion is considered. Fortunately, normal prints mimic steady-state extrusion as short periods of travel between deposition will maintain nozzle pressure. However, this does further reinforce that if nozzle pressure subsides during the print process for whatever reason, under extrusion could occur. Though this might suggest that to improve quality even if there are long travel distances in the g-code this pressure must be maintain through some other mechanism. Or quality might improve if the g-code generation favored print paths that minimize long travel distances.

**Conclusion & Outlook**

In conclusion, these results suggest that there is an ideal melt temperature and therefore an ideal viscosity that is low enough allow the material to flow out of the nozzle but not too low that sufficient pressure cannot be achieved within the nozzle within a reasonable period of time. For low volumetric flow rates, commonly seen during the first layer, the could be achieved with a lower nozzle temperature. For high volumetric flow rates with the 0.6 and 0.8 mm nozzle, this might require higher nozzle temperatures. Though this might not be ideal since this might induce large temperature gradients across the radius of the extrudate since the core will be cooler. This might suggest the necessity to pre-heat the filament or build nozzles with a longer heated zone to reach a temperature equilibrium with the extrudate. Regardless, the issue of under extrusion must be addressed if quality is to be less sensitive to print parameters. Finally, for any FFF research exploring the effects of print parameters on properties such as tensile strength, the influence on under extrusion on the results must be included. For example, one could print specimens at low volumetric flow rates and then claim this leads to weak parts; however, this would only be an artifact of the massive under extrusion.

Looking forward there is significant work required to better understand the extrusion process. While it is evident from these results that under extrusion can occur even within manufacturer recommended nozzle temperatures and maximum extrusion rates, this work did not explore why. To glean a better understanding of the phenomena occurring within the FFF nozzle, this process needs to either be modeled or simulated, ideally both. Therefore, better characterization of the materials used in the FFF process is necessary as material properties viscosity are required. Lastly, this work only explored one liquefier design with three nozzle diameters with one commercially available resin. Obviously, the non-Newtonian behavior of different grades or resins will be dramatically different. Looking at traditional extrusion, which has screws optimized for different polymers, it may be that nozzles must be optimized for each resin in the FFF system. However, without further work these questions cannot be answer.

In summary, this work presented a cursory attempt to begin to standardize a procedure to determine if a FFF printer is extruding at the expected rate, the results showed that increasing the temperature of the nozzle does not always yield increased throughput and lastly, for large diameter nozzles the material does not warm sufficiently when extrusion rates are high even when the nozzle temperature is well above the recommended temperatures.

**References**


