**Material Extrusion Volumetric Flow**

**Rate Analysis**

Identifying Hot End and Extruder Limitations in

High Speed Large Format 3D Printing

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M E 498 – Advanced Additive Manufacturing

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Abstract

In order to maximize the volumetric flow rate of material extrusion, a series of experiments were performed to test many of the variables that affect this rate. The parameters chosen for the tests were based on the hypothesis formed through preliminary research.

The purpose of this

[COMPLETE AFTER]

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Terminology

|  |  |
| --- | --- |
| Hot End | Active component of the printer that melts filament and extrudes the melted plastic onto the bed and part. |
| Heat Sink | Heat exchanger that actively dissipates heat from the hot end into the surrounding environment |
| Heat Break | Connection between heat sink and heater block that marks the transition from the hot to cold regions of a hot end. |
| Heater Block | Thermally conductive component that holds the heating element and temperature reading device. |
| Nozzle | Tip of the hot end with a small hole (0.40 mm is a common size) at which molten plastic is extruded. |
| Heater  Cartridge | A common heating element based on electrical resistance. Tube shaped. Used in testing. |
| Thermistor | Most commonly found temperature sensor. Resistor with significantly varying resistance values based on temperature. Monitor heat production to allow printer to keep constant temperature. |
| Extruder | Active component of printer that pulls filament from spool and feeds it into the hot end to be melted and extruded. Powered by stepper motor. |
| Idler | Part of an extruder that ensures filament is pushed against hobbed bolt. Usually tensioned using a spring. |
| Hobbed Bolt | Teethed bolt that grips filament. |
| Material  Extrusion | Most common form of additive manufacturing among 3D printer hobbyists and enthusiasts. Also known as fused deposition modeling (FDM) or fused filament fabrication (FFF). |
| Pronterface | G-Code sender application with graphical interface. Software used in testing to control printer and run basic functions. |
| Priming | Process of flushing old material out of the hot end to ensure continuous filament line. Done by extruding a small amount of plastic. |
| Die Swell | Phenomenon where extrudate is greater in size than the die size. |
| G-Code | This is the code that controls Advanced Additive Manufacturing machinery as well as CNC mills and specifies the direction to move in, how fast to move and can be used to change the settings on these machines. |
| Threading | At higher volumetric flow rates, as it becomes more challenging to extrude the filament the hob bolt begins to dig into the filament creating grooves. The term “threading” refers to when even the extruded filament displays theses grooves (appearing similar to the threads on a machine screw). This obviously occurs as since the extruded filament wasn’t heated to the appropriate temperature due to its quicker passage through the hot end because of the high extrusion speed. This can be minimized through increasing the extruder temperature. |
| Blobbing | This refers to a severe differential (more than a 25% difference) in extruded filament’s cross sectional diameter. For example, if 50mm of filament was being extruded and one cross section has a diameter of .6mm and another had a diameter of 1.2mm that would be labeled as “blobbing.” |
| Printer Calibration | A necessary step before every trial where we test that correct length is being extruded (more detail in prep section) |
| Pulled Through Filament  Failure Mode | This refers to how many millimeters of filament are pulled by the motor and the hob bolt.  This refers to one or more of the following.   * Loud motor grinding noise, with little extruded filament. For example if the specified length was 50mm(and printer is properly calibrated which it was before every trial) and only 10mm went through then that would be failure. * Blobbing is characterized as a failure mode. * Severe threading. * Not enough filament pulled through as measured in the calibrated settings. For example, if we had calibrated the printer to pull 50mm of filament and this was successfully happening at lower speeds then the a failure would be 10mm less than the calibration or lower was pulled through so if only 10mm was pulled through (which occurred for some of the trials) then it would have been a failure mode. |

1. Introduction

1.1 Purpose of Study

Many 3D printers today are capable of high speed linear motion. However, maximum acceleration is vastly different from maximum acceptable printing speed. The root of this apparent problem lies within the hot end and extruder assembly. Current configurations are simply not able to feed, melt, and extrude material quick enough to match the speed and acceleration of mechanical movement. This limiting factor is described as the volumetric flow rate of material extrusion, the key to greatly reducing print time.

The purpose of this study is to identify limiting variables and experimentally test for attributes that maximize overall volumetric flow rate of material extrusion.

1.2 Research Questions

* What is the main limiting factor preventing greater flow rate of material?
* Does one dominating factor or a combination of variables that make up this limit?
* What attributes of a hot end and extruder are ideal for reducing print time?

1.3 Delimitations

Experiments performed are purely material extrusion. This is only one of the major components involved with the goal of reducing print times. Keep in mind the printer must still be able to mechanically move at high acceleration. Information presented also does not address the adhesive or warping properties of the extruded material during real printing conditions.

1. Theory

2.1 Research

A large majority of preliminary research was performed online. The proposed theoretical optimizations are based on conclusions found through this research, consulting others, and previous experiences. Sources of research include WOOF members, professors, online articles, blog posts, manufacturer documentation, engineering drawings, and forum discussions.

2.2 Component Breakdown

2.2.1 Filament Diameter

Within the hot end and extruder sub-assembly there are two major determinants of material extrusion: the rate at which filament can be fed into the hot end and the rate at which the hot end is capable of melting filament and extruding that material.

Large format speed printing yearns for high volumetric flow rate. It may make intuitive sense to use larger filament for these prints. 3 mm diameter filament will indeed deliver more volume per length given the same extruder setup. However, feed rate is something that can be variably changed based on motor specifications, while melting rate is much more constrained. This means that the volumetric flow is primarily bound by the melting rate of plastic within the hot end. The extent of this boundary is not clearly defined and may even be beyond the limitations of the motor.

The greater the filament contact surface area per unit volume (SA:V ratio), the greater the ability to transfer heat. More and quicker heat transfer from the hot end melt-zone to the filament is essential to achieving a rapid melting rate. This basic thermodynamic design principle is also seen in computer heat sinks. They are composed of many very thin aluminum plates, because it optimizes the contact surface area with the surrounding cooling medium. This property can be applied both for cooling and heating objects.

The importance lies in the ratio between surface area and volume. The following chart compares the statistics of both filament sizes given the same volume of material:

**Filament Comparison for a Given Volume**

|  |  |  |
| --- | --- | --- |
| Filament Diameter | 1.75 mm | 3 mm |
| Sample Volume (V) | 1000 mm3 | 1000 mm3 |
| Filament Length Required (L) | 415.752 mm | 141.471 mm |
| Surface Area of Given Length (SA) | 2285.716 mm2 | 1333.333 mm2 |
| SA:V Ratio | 2.286 | 1.333 |

Surface area calculated is based only on the outer portion of the cylindrical filament that will be in contact with the walls inside the hot end.

The tradeoff becomes 1.71 times more SA:V and therefore quicker melting, for a minimum 2.94 times faster feed rate. If optimizing for volumetric flow rate, 1.75 mm has a decisive advantage given its ability to melt significantly faster. The problem is the extruder motor will need to run at least 3 times quicker.

If truly optimizing for absolute maximum print speed, a motor capable of high rotational speed as well as enough torque for constant extrusion and retraction and a proper cooling setup is needed to print with 1.75 mm.

2.2.2 Nozzle Orifice

An obvious solution to increasing the outgoing volumetric flow rate is to increase the orifice of the nozzle, allowing greater amounts of material to be extruded at once. This also leads to thicker maximum layer heights, but more importantly wider layer tracks. Wider tracks can increase layer adhesion and retain more heat to help reduce layer warping through uneven layer temperatures.

Due to the nature of a circular orifice, all external edges and corners will be filleted. It is very difficult to create external edges that are sharp with no roundness. Nozzle orifice diameter determines the radius of this fillet.

Increasing orifice diameter can dramatically decrease print times, but also decrease resolution due to larger layer heights and more round edges. This is a subjective tradeoff between time and resolution. In terms of volume flow, increasing nozzle orifice is an easy choice.

2.2.3 Melt-Zone Length

When talking about hot ends thermally, there are 3 major regions across the hot end: melt, transition, and cold zones.

The melt-zone is the hottest part of the hot end and consists of the heater block with the heater cartridge attached and the nozzle. As the name implies, this is where the filament melts and is pushed out the orifice. This region is absolutely vital to the print and can be modified to suit the goal of greater volumetric flow.

The length of the melt-zone controls the amount of molten plastic within the hot end at any given time. It also increases the residency time of filament within the melt-zone, ensuring that the heat transfer from the heater block and nozzle to filament has enough time to melt it fully.

2.2.4 Drive System

Newton’s second law states that the acceleration of an object is inversely proportional to its mass.

Reducing the mass on any moving part will reduce its inertia, thus reducing its resistance to change in velocity and increasing maximum acceleration. This aspect of the gantry system can still reduce print time even when limited by the hot end and extruder assembly. Moving acceleration is relevant when printing an object with separated bodies across any cross section. An example is printing a table. The legs are spaced out from one another. It may even be more time consuming to move to each location than to print the profile of the leg itself. While this aspect is not directly related to material extrusion, it is still a means of reducing print time.

One way to dramatically reduce mass on the hot end carriage is to implement a Bowden drive system. Remotely mounting the extruder and respective motor elsewhere, can cut the mass in half. The filament is then contained within PTFE tubing, a low friction thermoplastic which connects to the extruder and leads to the hot end itself.

Even though PTFE has one of the lowest friction coefficients, it is still an added force the extruder motor will need to overcome. The magnitude of this opposing force is determined by the quality of fitting with the corresponding filament size and the length of tubing from extruder to hot end.

The increased resistance requires a greater torque output from the motor. This will in turn reduce the maximum rotational speed of the motor, given by:

|  |  |
| --- | --- |
|  | (A) |

2.2.5 Filament Material and Quality

The two most common types of filament used are Acrylonitrile Butadiene Styrene (ABS) and Polylactic Acid (PLA). There exists other “exotic” variants of these thermoplastics, but are not as readily available. For the sake of availability and price, only these two materials will be assessed.

|  |  |  |
| --- | --- | --- |
| **Material** | **Thermal Conductivity**(W/m•K) | **Specific Heat Capacity** (J/kg•K) |
| **ABS** | 0.17 – 0.19 | 1080 – 1400 |
| **PLA** | 0.13 | 1800 |

**Specific Heat Capacity**

The amount of thermal energy (q) to raise a unit mass (m) of material by a unit of temperature (T) is described by its specific heat capacity (c). Units are Joules per kilogram per Kelvin.

A greater change in temperature is desired for more rapid melting of material. Therefore a lower specific heat capacity is ideal, given its inverse relationship with temperature change. ABS has a significantly lower specific heat capacity, meaning it requires less heat to be added for the same change in temperature of the same mass when compared to PLA.

**Thermal Conductivity**

What is even more important is the rate of transfer of thermal energy (Q/t) through a material per unit thickness (d) per unit temperature difference (T). This property is expressed as thermal conductivity (κ).

This is the equation for heat transfer through conduction. Heat conduction per unit of time is directly proportional to the material’s thermal conductivity. ABS has a higher thermal conductivity, thus it is the clear choice of material for melting the most rapidly.

2.2.6 Volumetric Flow Rate

Volumetric flow rate describes the rate of volume of filament that is inputted, melted, and outputted throughout the hot end.

Initially the first couple failure mode tests were performed by increasing the filament pulled rate in mm/s. However, after finalizing the various variables that were to be tested such as nozzle diameter, filament diameter etc. it was decided that such a procedure would yield puzzling data. For example, 3mm filament could failing at a lower rate than 1.75mm filament would lead to incorrect conclusions since this method of incrementing simply takes into account length and not volume. Thus, it was decided to measure by volumetric flow rate per trial in increments of 200 millimeters cubed per second. Here is the equation to find the volumetric flow rate from a filament of a certain diameter, where the speed of extrusion is multiplied by the cross sectional area of the filament.

2.3 Hypothesis

In the beginning, several predictions were made regarding performance of 1.75mm versus 3.00mm filament, ABS versus PLA material, and the V6 hot end versus the E3D Volcano. The 1.75mm filament was predicted to have a higher failure volumetric flow rate compared to the 3.00 filament since a smaller diameter means higher surface area to volume ratio making it easier to melt(as shown in the table above). This would allow it to be extruded at higher volumetric flow rates because while its being pulled fast it resides in the hot end for shorter amounts of time thus superior melting capabilities would allow it reach melting temperature even at higher rates. ABS was hypothesized to be extruded at a higher volumetric flow rate then PLA since it has higher thermal conductivity. Lastly, the Volcano was believed to allow for better extrusion since it is longer which allows the filament to reside in the hot end for a longer period of time thus it will heat up quicker and more uniform, earning higher volumetric flow rates.

1. Experiment

3.1 Set-Up

During experiments, it is important that the testing variable is the *only* variable. When there are more external factors, it is difficult to say with certainty X is caused by Y when in fact it could have been Z. Correct planning and execution will eliminate as many external variables as possible.

All testing was performed using a MakerFarm Prusa i3v printer. The microcontroller, cables, power supply, software, and computer were also the same in every test. Hot end and extruder set-up were the only factors changed. Experiments were all conducted in MEB G045 (WOOF 3D room).

Hot end products used were all created by E3D. Specifically the products used were E3D’s v6 All Metal Hot End and Volcano with their respective hardware. The choice of a single manufacturer is one of the most important decisions in testing, as it ensures machining quality is uniform across all products, eliminating the variable of different hot end quality and performance.

3.2 Procedure

To guarantee system consistency across all experiments, a series of pre-test procedures are carried out. Printers can be extremely sensitive to change, thus for each configuration these calibrations steps had to be performed.

3.2.1 Priming

Whenever filament is pulled out of the hot end for maintenance or swapping, not all of the material can be removed. There remains a small amount in the nozzle and heater block that has been melted. After reinserting filament, even if it is the same one removed, a discontinuity is introduced. There may be a gap in between the old material and the new.

Hot end “priming” involves completely flushing out this old material through extrusion, and extruding a small amount of the new filament. This re-establishes the continuous filament line from the tip of nozzle to the spool and ensures that the inserted filament is the only extruded material. Additionally, after even a short amount of time the molten plastic in the nozzle tip will ooze on its own due to gravitational forces.

Priming was done at any point filament is reinserted and after the extruder has been idle for over 60 seconds. Priming is done to make sure there are no gaps of material throughout the entirety of the hot end assembly. Without this step, the length of the extrudate may be shorter than it would be otherwise, skewing our results.

3.2.2 Extruder Motor Calibration

The steps per millimeter value written in the firmware is a direct correlation between inputted length to be extruded and duration of motor shaft rotation. If this setting is not set correctly, the extruder can pull less than half or even greater than double the filament length it is told to.

More importantly, the rotational speed of the motor is based off of this value. Proper calibration involves iteratively comparing the set length of filament to be extruded and the actual length of filament pulled by the extruder. Adjustments are made until these two values are within a set margin.

Explanation of exact extruder calibration is expanded upon in Appendix A.

3.2.3 Steps

1. Prepare the printer with the necessary hot end, filament, extruder, temperature etc.
2. Extrude 50mm of filament at the specified speed in mm/s specified in the table.
3. Diligently monitor the hob bolt for stripped filament or skipping of the motor. Note grinding or whining sounds from the motor.
4. Keep turning the filament spool so sufficient slack is maintained to prevent the filament from snapping.
5. Depending on the trial measure the diameter/length of the extruded filament, or measure the length of the extruded filament.
6. If moderate die swell/blobbing occurs or extruded length/pulled length is a little less than at the control volumetric flow rate of 200, then give the trial a rating of 2. If the conditions are the exact same as the volumetric flow rate of 200 then give a 1. Lastly, if the extruded filament exhibits severe blobbing or pulled filament is much less than 50 mm (around 50% error from the control) then give trial an X which represents failure.
7. Repeat steps 2-6 five times then move onto the next volumetric flow rate.
8. Testing Results

The following tables each contain a header table including the details of the configuration. In all experiments there are up to 7 variables that can be changed. Identifying the configuration in each test is important to understanding the experimental findings. Tables will be compared to one another. The variables are explained below and shown with their possible values.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **MELT** | Length of the melt-zone   * 16 mm (E3D v6) * 22 mm (E3D Volcano) | | **MATERIAL** | Filament material   * ABS * PLA |
| **DRIVE** | Drive system   * Direct Drive * Bowden | | **TEMP** | Set hot end temperature   * 190 – 270 °C |
| **DIAMETER** | Filament diameter   * 1.75 mm * 3.00 mm | | **LENGTH** | Filament length fed   * 25 - 200 mm |
| **ORIFICE** | Nozzle orifice diameter | |  |  |
|  | * 0.4 mm * 0.6 mm * 0.8 mm | * 1.0 mm * 1.2 mm |  |  |

4.1 Table 1 – Maximum Flow Rate without Failure

**Data**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| MELT | DRIVE | DIAMETER | ORIFICE | MATERIAL | TEMP | LENGTH |
| Volcano | Direct | 1.75 mm | 1.2 mm | ABS | 240 C | 50 mm |

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Flow Rate (mm3/min)** | **Speed**  **(mm2/min)** | **Trial 1** | **Trial 2** | **Trial 3** | **Trial 4** | **Trial 5** | **Avg.**  **Value** |
| **200** | 83.15 | 1 | 1 | 1 | 1 | 1 | 1 |
| **400** | 166.30 | 1 | 1 | 1 | 1 | 1 | 1 |
| **600** | 249.45 | 1 | 1 | 1 | 1 | 1 | 1 |
| **800** | 332.60 | 1 | 1 | 1 | 1 | 1 | 1 |
| **1000** | 415.75 | 1 | 1 | 1 | 1 | 1 | 1 |
| **1200** | 498.90 | 1 | 1 | 1 | 1 | 1 | 1 |
| **1400** | 582.05 | 1 | 1 | 1 | 1 | 1 | 1 |
| **1600** | 665.20 | 1 | 1 | 1 | 1 | 1 | 1 |
| **1800** | 748.35 | 2 | 2 | 2 | 2 | 2 | 2 |
| **2000** | 831.50 | 3 | 2 | 2 | 2 | 2 | 2.2 |
| **2200** | 914.65 | X | 3 | X | 3 | 3 | 3.4 |
| **2400** | 997.80 | X | X | X | X | X | - |
| **2600** | 1080.96 | X | X | X | X | X | - |
| **2800** | 1164.11 | X | X | X | X | X | - |
| **3000** | 1247.26 | X | X | X | X | X | - |

**Failure Mode:** Stepper motor cannot exceed ~870 mm/min

* 1: (Good) Best extrusion, constant, even (despite air bubbles)
* 2: (Minor) Failure mode beginning to show, somewhat constant extrusion (minor)
* 3: (Major) Motor skips steps, loud grinding­ noise, does not function properly
* X: (Failure) Complete failure, does not extrude at all

1. Analysis

Die Swell

Stepper Motor and Driver Limitations

Extruder Design

In the hobbyist and enthusiast world, printed extruder parts are extremely common. Without the quality control and high standards found in the hot end market, there is more room for problems to occur.

An example of

1. Appendix

6.1 Appendix A - Calculations

Calibrating Extruder Steps

Extruder steps per millimeter must be properly calibrated before testing. The NEMA 17 stepper motor used in testing is capable of 200 steps per revolution. This translates to a 1.8° rotation of the shaft per step. The value E, in steps per millimeter, defines for the printer the number of steps required to feed length L in millimeters of filament. The procedure to proper calibration consists of instructing the printer to extrude a set length of material and measuring the actual length fed. The following equation is used:

|  |  |
| --- | --- |
|  | (1) |

Where Enew is the new steps per millimeter value to input to the printer to properly calibrate the extruder, Lset is the set length of filament to be extruded, Lactual is the actual length of filament pulled, and Ecurrent is the current extruder value.

Calibration for these experiments all follow the same procedure. From a known point, 150 mm of filament is marked. Using Pronterface, a printer G-CODE sender, the printer is instructed to extrude 100 mm of filament at a set slow speed known to work without failure. After extruding, the length from the mark to the known point is measured. If properly calibrated, this value Lmeasured should be exactly 50 mm. Otherwise:

|  |  |
| --- | --- |
|  | (2) |

For example, after instructed to extrude 100 mm, the actual measured length of filament fed is 125 mm. This gives the **extruder multiplier** of 0.8 that is multiplied with the current extruder value, to give the new steps per millimeter as seen in Equation (1).

This process is repeated until a single value of steps per millimeter passes two trials of measurement at 100 mm of filament fed with a tolerance of ±1.00 mm.

Filament Diameter

6.2 Appendix B – Printrun Software

6.2.1 Automating Calibration with Macros

Inputting G-CODE, manually typing extruded filament length, and setting extrusion speed for every calibration became an exceedingly tedious task. Luckily, Pronterface is a public repository on GitHub that is free to fork. This software can be modified and custom buttons and input fields added to automate the software side of the calibration process.

Pronterface also includes the ability to include custom macros. The reason why this is truly powerful is it allows the user to integrate Python code with the G-CODE macro, making it easier to execute program logic. Several Python scripts were written to automate calibration and testing.

First, three simple buttons were added to Pronterface labeled “800 steps,” “700 steps,” and “600 steps,” and each of these sets the extruder steps value to the number on the button. Then the material would be extruded and the pulled amount would be measured and then the macro “calibrate extruder” would be called by passing in the arguments for the “[set extruded length] [actual extruded length] [steps number]” and then this would automatically generate the G-CODE using the calibration formula for a very accurate printer steps calibration. This code as well as some of the other macros are attached below.

6.2.2 Macros for Calibration

The first macro accepts the first 3 parameters from the command line and then calls the macro for the G-CODE with the calculated steps value and then that one calls it with the {0} which represents the first passed argument.

Macro: calibrate\_extruder

!set = float(arg[0])

!actual = float(arg[1])

!steps = int(arg[2])

!val = set/actual \* steps

!val = int(val)

calibrate\_extruder\_gcode val

Macro: calibrate\_extruder\_gcode

M92 E{0}

Macros for Increasing Volumetric Flow Rate

This macro seamlessly integrates the Python for loop and extrudes 50mm of filament at “val” speed and keeps aggregating its value while sleeping in the middle to provide adequate time to note observations and measurements.

Macro: extrude\_filament\_faster

!for i in range(0,10):

! val = 83.15 + 83.15\*i

;@ extrude length val

! sleep(5)

Macros for Increasing Extrusion Temperature

This macro uses a while loop and will increase the temperature by 10 extrude and then increase by ten again and essentially extrude 50 mm of filament at the failure speed. There is no need for an explicit delay or sleep call since the time it takes to heat up by 10 degrees allows for enough room to note down measurements and observations.

Macro: extrude\_filament\_higher\_temp

!val = 190

!targetVal = val + 10

!while(targetVal < 270):

! val = @; gettemp

! if(val == targetVal):

;@ extrude length 914

! targetVal = targetVal + 10

;@ settemp targetVal

6.3 Appendix C – Die Swell

Die swell is a common phenomenon evident in 3D printing and other forms of polymer extrusion in which the extruded material is greater in diameter than the die. The polymer stream is compressed upon entrance into the barrel of the hot end nozzle and “swells” back to its original shape after exiting.

The extent of swelling is expressed as B, the die-swell ratio of extrudate diameter to die diameter.

|  |  |
| --- | --- |
|  | (A) |