**Hot End and Extruder Volumetric Flow**

**Analysis**

Theory and Design Analysis for High Speed Large Format 3D Printing

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Hot End and Extruder Volumetric Flow Analysis

Theory and Design Analysis for High Speed Large Format 3D Printing

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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 effect this rate. The parameters chosen for the tests were based on our hypothesis formed through preliminary research.

[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  Threading  Blobbing  Printer Calibration  Pulled Through Filament  Failure Mode  def | 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.  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.  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.”  A necessary step before every trial where we test that correct length is being extruded(more detail in prep section)  This refers to how many millimeters of filament is 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.   def |
|  |  |

Introduction

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 ensure maximum overall volumetric flow rate of material extrusion.

Research Questions

* What is the main limiting factor preventing greater flow rate of material?
* Is it 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?

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 an actual print.

Theory

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 online articles, blog posts, manufacturer documentation, engineering drawings, and forum discussions.

Component Breakdown

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 contact surface area with the hot end per unit volume of filament (SA:V ratio), the greater the ability to transfer heat per volume. 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.

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. This also leads to thicker maximum layer heights, but more importantly wider layer tracks. Wider tracks means greater layer adhesion as well as the ability to retain more heat and can help reduce layer warping through uneven layer temperatures. Larger nozzles orifices will lead to lower resolution. The tradeoff between resolution and speed is subjective.

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.

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.

Depending on the gantry system, in order to increase acceleration of the hot end carriage mass must be removed from the unit.

One solution is to implement a Bowden drive system. The remotely mounted extruder and respective motor will greatly reduce the moving mass on the hot end, considering that a NEMA 17 stepper motor is 300-400 g.

Filament Material and Quality

Volumetric Flow Rate

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.

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.

Experiment

Set-Up

During experiments, it is important that the testing variable is the only variable. When there are more than one external factors, it is difficult to say with certainty X is caused by Y when in fact it could have been Z.

All testing was performed using a MakerFarm Prusa i3v 8”. 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 change. Experiments were all conducted in MEB G045 (WOOF 3D room).

The 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 that the machining quality is the same and eliminates the variable of different hot end quality and performance.

Procedure

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.

Testing Results

Table 1

Data

[insert table here]

Specifications

[Changed variables, specific things worth noting (e.g. Octave 1.75mm yellow ABS)]

Findings

[e.g. filament stripping @ 1800 flow rate; motor limiting factor, etc.]

Table 2

…

Cover the results from pure motor failure

Basically going to cover results from the threading and how that leads then moving to high temperature trials

An important observation was made in Table 2 (the trial with 1.75mm ABS orifice 1.2mm) as well as Table 3(the trial with 1.75 mm PLA with the orifice of 0.6mm). The failure mode for Table two occurred at the volumetric flow rate of 2200 where loud motor grinding noises where heard, the extruded filament came out significantly slower than the previous rate, and there was threading on the extruded filament. For table 3 the failure mode was threading as well as severe blobbing. Initially this was thought as a failure of the motor however after further analysis it was deduced that if the filament was appropriately melting there shouldn’t be any threading at all because extruded filament has homogenous texture. Thus a new set of tests was incorporated in which it was decided that the filament would be extruded at the failure rate while increasing the temperature in 10 minutes as if the filament is extruded really fast it doesn’t spend sufficient time in the hot end so isn’t actually heated to the necessary 190 or 240 degrees and might actually be extruded at around 150 or 220 and thus doesn’t have the homogenous consistency.

-I want to write a quick g-code calibration script in free time, you enter the value its supposed to extrude and then how much it did, its current step setting, and then it generates the correct amount Gcode for you and inputs it into the command. Will look into the source on github and make a in program mod, if not can write a separate script

Rough Testing Results Outline:

1st set of trials was essentially pla vs abs, and 1.75mm and 3.00mm

abs vs pla no affirmative sets of data,

1.75 vs 3.00 mm roughly the same (could do a more precise set of tests)

(basically have a possible explanation for pla vs abs, for 1.75mm vs 3.00mm)

blame the motor for this issue

2nd

Temperature vs the maximum failure rate

Success as filament pulled through

3rd

Better more efficient motor setup and how that actually ends up affecting the maximum volumetric flow rate

Due this same trial for this motor possibly with a higher temperature

Analysis

Die Swell

Die swell is a 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 the polymer “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) |

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

Appendix

Appendix A - Calculations

Calibrating Extruder Steps

It is essential the extruder steps per millimeter is properly calibrated before testing. The NEMA 17 stepper motor used 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, Lmeasured 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** 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

Appendix B – Printrun Software

Automating Calibration with Macros

Inputting G-Code for every calibration and manually inputting the extruded filament length as well as extrusion speed became exceedingly tedious after many tests thus it was decided to fork the Pronterface repository and then add some custom buttons and fields to automate the calibration process and write scripts to run the various tests.

However, after reading through the source code and documentation it was realized that Pronterface includes the capability to include custom macros, but the reason why this is truly powerful is it allows the user to integrate python with the gCode macro making it easier to execute program logic. Because of this source wasn’t modified instead 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.

Appendix C – Die Swell