**Material Extrusion Volumetric Flow**

**Rate Analysis**

Identifying Hot End and Extruder Limitations in

High Speed Large Format 3D Printing

|  |  |
| --- | --- |
| Alan Ng  University of Washington  alan5@u.washington.edu | Rajas Agashe  University of Washington  rajas@cs.washington.edu |

Winter 2015

M E 498 – Advanced Additive Manufacturing

Material Extrusion Volumetric Flow Rate Analysis

Identifying Hot End and Extruder Limitations in

High Speed Large Format 3D Printing

Alan Ng

Rajas Agashe

Winter 2015

M E 498 – Advanced Additive Manufacturing

Instructor: Mark Ganter

Washington Open Object Fabricators

University of Washington

Abstract

Maximizing volumetric flow rate of filament is key to greatly reducing printing times in material extrusion 3D printers. A series of experiments were constructed and performed to identify variables that affect this rate. The parameters chosen for tests were based on the hypothesis formed through preliminary research.

Initially it was believed the melting rate of the hot end was the main limitation. It was expected that changing the values of the variables would clearly show the differences in volume output. The limiting components varied from trial to trial, however these differences were dependent on filament size.

With 1.75 mm filament the extruder set-up was the limiting factor. Lack of motor speed because of the motor specifications themselves or weak stepper drivers and hobbed gear slipping were the main modes of failure.

With 3.00 mm filament the hot end was the limiting factor. The main mode of failure was shown by the hobbed bolt stripping the filament. If the teeth of the bolt chew up the filament, it means the bolt is able to grip and pull the filament, but the filament showed resistance because it could not be melted quick enough to be extruded.

In all cases, there is not a single dominating limitation, but rather a combination of limits depending on the set-up. The results mostly confirmed the hypothesis.

Acknowledgements

We would like to thank the Washington Open Object Fabricators (WOOF 3D) club for their valuable contributions, use of space, and lending of research materials. Additionally we thank Mark Ganter, Steve Weidner, and Jeff Bergeson for their direct input that greatly assisted our research.

Table of Contents

**Terminology1**

**1 Introduction3**

1.1 Purpose of Study3

1.2 Research Questions3

1.3 Delimitations3

**2. Theory4**

2.1 Research4

2.2 Component Breakdown4

2.2.1 Filament Diameter4

2.2.2 Nozzle Orifice 5

2.2.3 Melt-Zone Length6

2.2.4 Drive System6

2.2.5 Filament Material and Quality7

2.2.6 Volumetric Flow Rate8

2.3 Hypothesis8

**3. Experiment9**

3.1 Set-Up9

3.2 Procedure9

3.2.1 Priming9

3.2.2 Extruder Motor Calibration10

3.2.3 Steps10

**4. Testing Results11**

4.1 Table 112

4.2 Table 213

4.3 Table 314

4.4 Table 416

4.5 Table 5-

4.6 Table 617

4.7 Table 718

4.8 Table 819

4.9 Table 921

4.10 Table 1023

4.11 Table 1125

**5. Analysis27**

3.1 Findings27

3.2 Conclusions29

**6. Appendix30**

6.1 Appendix A – Calculations30

6.2 Appendix B – Printrun Software31

6.2.1 Automating Calibration with Macros31

6.2.2 Macros for Calibration31

6.3 Appendix C – Die Swell33

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 | 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 | Small grooves apparent on extruded filament, similar to the threads on a machine screw. Occurs when extruded filament wasn’t heated to the appropriate temperature due to its quicker passage through the hot end. |
| Blobbing | Severe differential (>25% difference) in the extruded filament’s cross sectional diameter due to die swell. |
| Printer Calibration | A necessary step before every trial where we test that correct length is being extruded (more detail in prep section) |
| Pulled  Filament | Length of filament in millimeters pulled by the hobbed bolt of the extruder. |
| Failure Mode | Particular form of failure that varies from trial to trial. |

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. The goal of this project is to assess limitations in terms of only material output.

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

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. If the melt-zone is too short, the cold plastic that is constantly shoved through the hot end will act as a cooling agent and will lower the temperature of the hot end.

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 legs themselves. While this aspect is not directly related to material flow, 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 that connects to the extruder and leads to the hot end itself.

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

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:

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 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 in terms of volume output.

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 increasing the filament pulled rate in mm/s performed the first couple failure mode tests. 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 failing at a lower speed 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 production 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 out 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 results.

3.2.2 Extruder Motor Calibration

The step 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. Carry out above calibration steps
3. Extrude 50 mm of filament at the specified speed in mm/s specified in the table.
4. Diligently monitor the hobbed bolt for stripped filament or skipping of the motor. Note grinding or whining sounds from the motor.
5. Keep turning the filament spool so sufficient slack is maintained to prevent the filament from snapping.
6. Depending on the trial measure the diameter/length of the extruded filament, or measure the length of the extruded filament.
7. 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 that represents failure.
8. Repeat steps 2-6 five times then move onto the next volumetric flow rate.
9. 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 | | **FLOW** | Volumetric flow rate |
|  | * 0.4 mm * 0.6 mm * 0.8 mm | * 1.0 mm * 1.2 mm |  | * 200 – 3000 mm3 |

4.1 Table 1 – Maximum Volumetric Flow Rate

**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

**Specifications:**

* 1.75 mm Black Octave ABS Filament

**Observations**

* “Bubbles” found in extrudate in all trials
* Filament is water contaminated, producing air bubbles in all extrusions
* Filament quality greatly effects extrusion quality

4.2 Table 2 – Maximum Volumetric Flow Rate

**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 | 1 | 2 | 1 | 2 | 1 | 1.4 |
| **2000** | 831.50 | 1 | 1 | 1 | 1 | 1 | 1 |
| **2200** | 914.65 | X | X | X | X | X | - |
| **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 ~914 mm/min

* 1: Best extrusion
* 2: Extrusion (minor threading or blobbing)
* X: Complete failure, does not extrude at all (fail)

**Notes/Observations:**

* Clicking noise on motor starts on the first trial.
* At 750 mm/s minor blobbing begins to occur as well as minor threading (intermittent occurrence). Blobbing occurs around every 30mm even if the extruded length is increased.
* The 831 mm/s doesn’t cause any blobbing but loud motor grinding noise heard and stepping visible thus really extruding at a smaller volumetric flow rate.
* At 914 high grinding noise heard, and wheels barely turn and no filament extruded thus motor failure had occurred due to lack of motor torque at high speeds.
* Important observation is that no need for number 3 on the rating scheme because extrusion quality goes from minor blobbing and threading to sudden failure.
* Failure for ABS (this trial) occurs at the same volumetric flow rate as for PLA, thus although this material has higher thermal conductivity than PLA, its not enough to heat up to 240 fast enough to offset the higher motor speeds. Or it can still melt but the motor doesn’t have enough torque at higher speeds to push the filament through. However, since threading was visible the limitation for this trial probably is the filament not being able to get hot enough rather than the motor lacking torque.

**Specifications:**

* 1.75 mm ABS Octave Yellow branded (poor history as oxygen has been trapping)
* E3D Volcano 1.2mm Orifice
* Spring Tension: (~58.70 mm for 3mm) (~58.90 mm for 1.75mm)

4.3 Table 3 - Maximum Volumetric Flow Rate

**Data**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| MELT | DRIVE | DIAMETER | ORIFICE | MATERIAL | TEMP | LENGTH |
| Volcano | Direct | 1.75 mm | 1.2 mm | PLA | 190 °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 | 2 | 2 | 2 | 2 | 2 | 2 |
| **1800** | 748.35 | 2 | 2 | 2 | 2 | 2 | 2 |
| **2000** | 831.50 | 1 | 1 | 1 | 1 | 1 | 1 |
| **2200** | 914.65 | X | X | X | X | X | X |
| **2400** | 997.80 |  |  |  |  |  |  |
| **2600** | 1080.96 |  |  |  |  |  |  |
| **2800** | 1164.11 |  |  |  |  |  |  |
| **3000** | 1247.26 |  |  |  |  |  |  |

**Notes/Analysis:**

* Initially there was buckling around the 665 flow rate so it was attributed to a smaller length in tubing that wasn’t covering all the filament, so tubing was increased in length to circumvent this problem.
* For 665.2 speed, roughly after 76 mm the extruded filament starts to fail as it has blobs, deformed shape, with some threading, and motor grinding noise is heard with a couple skipped steps.
* For 748 same 76mm failure length as above.
* At 831 severe motor grinding noises but extrusion is flawless indicating the skipping steps mimicking a trial at a lower speed.
* Failure at 914, high grinding noise and very little filament extruded. Motor failure as with the smaller tip there is higher pressure required to push the filament through and not enough torque to push it.

**Specifications:**

* 1.75mm Unknown Red PLA @ 190
* E3D Volcano 1.2mm Orifice
* Spring Tension: (~58.70 mm for 3mm) (~58.90 mm for 1.75mm)

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

* 1: Best extrusion
* 2: Blobbing occurs (minor)
* X: Complete failure, does not extrude at all (fail)

4.4 Table 4 - Maximum Volumetric Flow Rate

Data

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| MELT | DRIVE | DIAMETER | ORIFICE | MATERIAL | TEMP | LENGTH |
| Volcano | Direct | 1.75 mm | 1.2 mm | PLA | 190 °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 | 2 | 1 | 2 | 1.4 |
| **1800** | 748.35 | 2 | 2 | 2 | 2 | 2 | 2 |
| **2000** | 831.50 | 1 | 1 | 1 | 1 | 1 | 1 |
| **2200** | 914.65 | X | X | X | X | X | - |
| **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 | - |

**Notes/Observations:**

* At 665.2 minor threading begins to occur near the end of extrusion around a 10mm patch.
* At 748 the maximum threading occurs because this is the maximum speed at which the motor can push the filament through. Threading occurs near last 25mm and continues if extrusion length increased.
* At 831 clean trials occurs because the motor has gone past its actual limit so it extrudes as if it is extruding at a lower speed. This is proven by the grinding noise of the motor and the twitching suggesting that it is skipping steps.
* Failure mode occurs at 914.65, and severe motor grinding noise is heard, and motor gears move very slowly suggesting that failure is in lack of motor power to push the filament through as well as filament not sufficiently heated due to the threading visible around the 748mm/min speed.

**Specifications:**

* 1.75mm Unknown Red PLA @ 190 instead of 3.0mm
* 1.2mm E3D Volcano nozzle
* Spring Tension: (~58.70 mm for 3mm) (~58.90 mm for 1.75mm)

**Failure Mode:**

* 1: Best extrusion
* 2: Grinding Noise, skipping (minor)
* X: Complete failure, does not extrude at all (fail)

4.6 Table 6 - Maximum Volumetric Flow Rate

**Data**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| MELT | DRIVE | DIAMETER | ORIFICE | MATERIAL | TEMP | LENGTH |
| Volcano | Direct | 3.00 mm | 1.2 mm | PLA | 240 C | 50 mm |

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Speed (mm/min)** | **Trial 1** | **Trial 2** | **Trial 3** | **Trial 4** | **Trial 5** | **Trial 6** | **Trial 7** | **Trial 8** |
| **50** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **75** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **100** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **125** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **150** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **175** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **200** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **225** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **250** | 1 | 1 | 2 | 2 | 2 |  |  |  |
| **275** | X | X |  |  |  |  |  |  |
| **300** | X | X |  |  |  |  |  |  |
| **325** | X | X |  |  |  |  |  |  |
| **350** | X | X |  |  |  |  |  |  |
| **375** |  |  |  |  |  |  |  |  |
| **400** |  |  |  |  |  |  |  |  |

**Observations:**

* Initially minor blobbing occurred at 250, but after replacing the stepper controller with a heat sink the blobbing occurs a few times beginning at 225, so the maximum speed for consistent extrusion occurs 200.
* Die swell very evident in this trial as the near the end of the extrusions that filament gets noticeably thicker in diameter.

Specifications

* 3.00 mm Unknown Red PLA @ 190
* 1.2mm E3D Volcano nozzle
* Spring Tension: (~58.70 mm for 3mm) (~58.90 mm for 1.75mm)

**Failure Mode:**

* 1: Best extrusion
* 2: Minimal Blobbing (minor)
* X: Difference in thickness of extrusions roughly 25% deviation (fail)

4.7 Table 7 – Pulled Filament Length at Varying Temperatures

**Data**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| MELT | DRIVE | DIAMETER | ORIFICE | MATERIAL | FLOW | LENGTH |
| Volcano | Direct | 1.75 mm | 1.2 mm | ABS | 2200 mm3/min | 50 mm |

|  |  |
| --- | --- |
| **Temperature (°C)** | **Length of Pulled Filament (mm)** |
| **240** | 9.28 |
| **250** | 16.34 |
| **260** | 18.48 |
| **270** | 20.50 |

Rate of pulled filament/increase in temperature is 0.374 mm/°C

**Summary:**

* After noticing that at the failure rates, less than the specified filament was pulled, we decided to measure the pulled filament at the failure flow rate as the temperature was increased.

**Notes/Observations:**

* We noticed that as the temperature increased the motor grinding noise became noticeably less audible.
* The explanation for the lack of filament being pulled in general has a two-fold explanation. First, the motor is reaching its maximum speed so the torque is decreasing thus it can no longer exert the force to drive the filament. The second explanation is that the since the filament is moving so fast it doesn’t spend enough time in the hot end to heat up to its melting point. This data shows that the pulled filament length increased by about 10mm from 240 all the way to 270. Thus it is shown that the of extruder temperature does contribute to an lower failure volumetric flow rate hence increasing the temperature allows for the filament passing through the hot end at high speeds reach a temperature closer to its actual melting point.
* An important observation is that the pulled filament by increase in temperature rate for ABS is 3 times the size of that for PLA. The reason for this is contained in theory 2.25. The higher thermal conductivity for ABS and the lower specific heat capacity results in a greater change in temperature thus ABS melts more the higher the temperature increases compared to PLA thus the rate of filament pulled for ABS is 3 times higher for every degree increase in temperature.

**Specifications:**

* Yellow Octave ABS 1.75mm
* 1.2mm orifice, E3D volcano
* Spring Tension: (~58.70 mm for 3mm) (~58.90 mm for 1.75mm)

4.8 Table 8 - Pulled Filament Length at Varying Temperature

**Data**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| MELT | DRIVE | DIAMETER | ORIFICE | MATERIAL | FLOW | LENGTH |
| Volcano | Direct | 1.75 mm | 1.2 mm | PLA | 2200 mm3/min | 50 mm |

|  |  |
| --- | --- |
| **Temperature (°C)** | **Length of Pulled Filament (mm)** |
| **190** | 14.39 |
| **200** | 16.92 |
| **210** | 16.90 |
| **220** | 23.11 |
| **230** | 22.00 |
| **240** | 22.35 |
| **250** | 24.11 |
| **260** | 26.52 |
| **270** | 29.43 |

Rate of pulled filament over increase in temperature is 0.188 mm/°C

**Summary:**

* After noticing that at the failure rates less than the specified filament was pulled, we decided to measure the pulled filament at the failure flow rate as the temperature was increased.

**Notes/Observations:**

* We noticed that as the temperature increased the motor grinding noise became noticeably less audible.
* The explanation for the lack of filament being pulled in general has a two-fold explanation. First, the motor is reaching its maximum speed so the torque is decreasing thus it can no longer exert the force to drive the filament. The second explanation is that the since the filament is moving so fast it doesn’t spend enough time in the hot end to heat up to its melting point. This data shows that the pulled filament length increased by about 15mm from 190 all the way to 270. Thus it is shown that the of extruder temperature does contribute to an lower failure volumetric flow rate hence increasing the temperature allows for the filament passing through the hot end at high speeds reach a temperature closer to its actual melting point.
* An interesting observation is that for this trial, over a temperature differential of 80 degrees Celsius, the extruded length increased by 15mm while for the ABS over a temperature differential of 30 degrees the extruded length increased by 10mm.
* Our theory (2.25) was correct in that the higher thermal conductivity for ABS and the lower specific heat capacity results in a greater change in temperature thus ABS melts more the higher the temperature increases compared to PLA thus the rate of filament pulled for ABS is 3 times higher for every degree increase in temperature.

**Specifications:**

* Unknown Red PLA 1.75mm
* 1.2mm orifice, E3D volcano
* Spring Tension: (~58.70 mm for 3mm) (~58.90 mm for 1.75mm)

**Failure Mode:** Not applicable as whole test is run at failure speed.

4.9 Table 9 – Extruded Length and Diameter at Varying Temperature

**Data**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| MELT | DRIVE | DIAMETER | ORIFICE | MATERIAL | FLOW | LENGTH |
| V6 | Direct | 1.75 mm | 0.6 mm | PLA | 2200 mm3/min | 50 mm |

|  |  |  |  |
| --- | --- | --- | --- |
| **Temperature (°C)** | **Cross Section Diameter (mm)** | **Die Swell Ratio**  **(B)** | **Extruded Length (mm)** |
| **190** | 0.98 | 1.63 | 76 |
| **200** | 0.80 | 1.33 | 90 |
| **210** | 0.75 | 1.25 | 96 |
| **220** | 0.67 | 1.12 | 99 |
| **230** | 0.64 | 1.06 | 108 |
| **240** | 0.62 | 1.03 | 116 |
| **250** | 0.61 | 1.01 | 124 |
| **260** | 0.60 | 1.00 | 158 |

**Notes/Observations:**

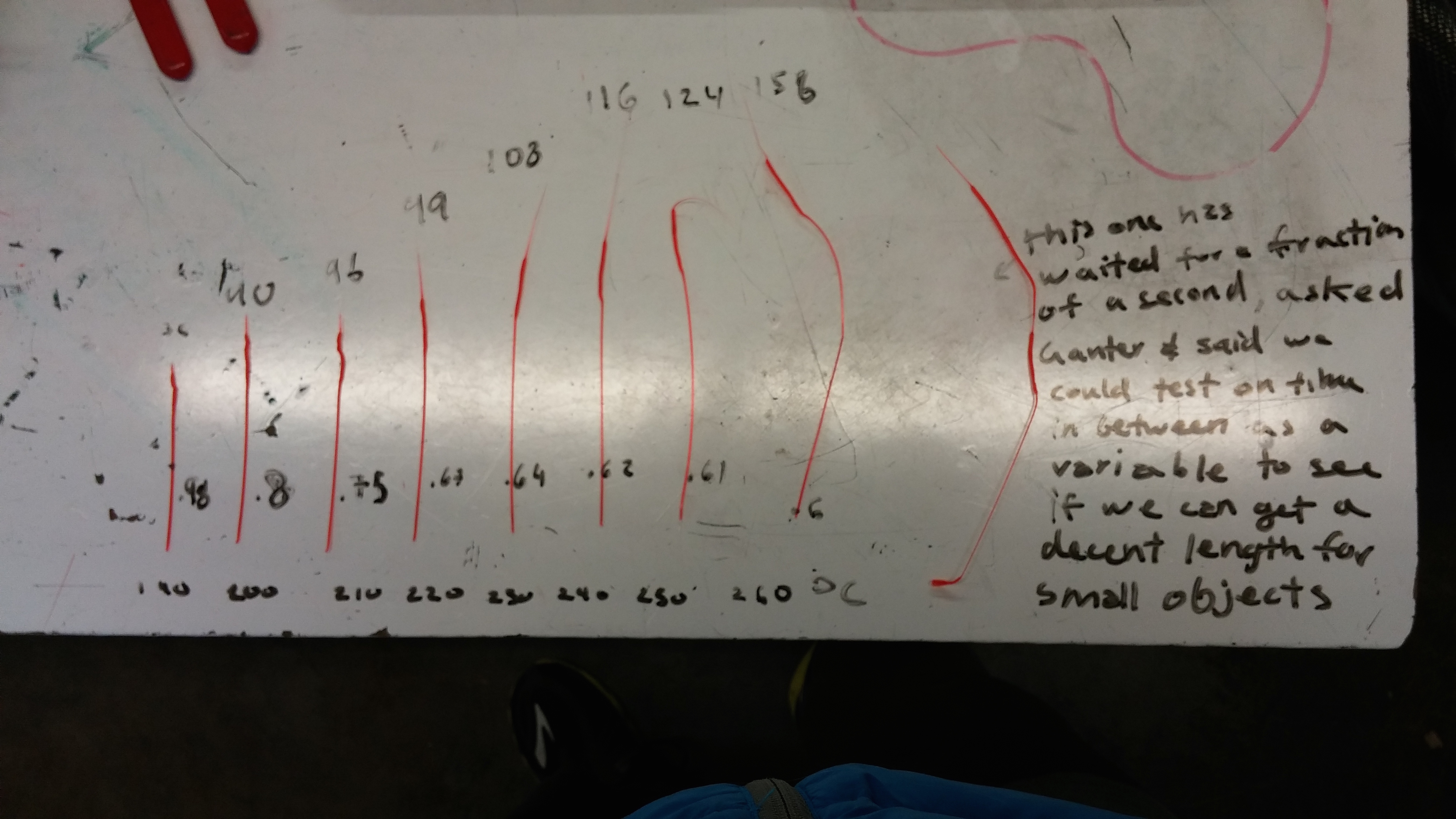
* For each trial a certain length is extruded at a diameter as noted in the table, however after that extruded length failure occurs for every trial as motor grinding noise heard, filament gets noticeably thicker, and hardly any filament is extruded.
* Extruded length increases for higher temperatures since the increased temperature is more conducive towards the filament melting so it can escape the hot end quicker.
* In the trial at 190 degrees Celsius greatest degree die swell occurs because the diameter is .98mm which is greater than the nozzle orifice of 0.6mm, however as the temperature increases the die swell reduces as the diameter at 260 degrees is equal to the diameter of the nozzle itself.
* However, it is important to note that at the end of a certain length of the extruded filament (as seen in the picture below) die swell begins to reoccur as the diameter of the extruded filament becomes noticeably thicker. This occurs since the filament was sitting in the hot end beforehand it is sufficiently melted, however, but once the motor starts the filament near the end doesn’t spend as much time in the hot end as did the filament in the beginning thus it doesn’t get hot enough and failure as well as die swell occur.
* It is important to note that increasing the temperature did not prevent failure, just alleviated the extent of the failure as occurrence of die swell in the beginning is avoided completely at high temperatures as .6 was the cross section diameter for 260, and its occurrence later is delayed as the extruded length (before major die swell) grows steadily for each temperature.

**Specifications:**

* 1.75 Unknown red PLA filament @ 190
* V6 nozzle with 0.6mm orifice
* Spring Tension: (~58.70 mm for 3mm) (~58.90 mm for 1.75mm)

**Failure Mode:** Not Applicable

**Photo**



4.10 Table 10 – Extruded Length and Diameter at Varying Temperature

**Data**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| MELT | DRIVE | DIAMETER | ORIFICE | MATERIAL | FLOW | LENGTH |
| V6 | Direct | 1.75 mm | 0.6 mm | ABS | 2200 mm3/min | 50 mm |

|  |  |  |  |
| --- | --- | --- | --- |
| **Temperature (°C)** | **Cross Section Diameter (mm)** | **Die Swell Ratio**  **(B)** | **Extruded Length (mm)** |
| **240** | .74 | 1.23 | 63 |
| **250** | .68 | 1.13 | 71 |
| **260** | .65 | 1.08 | 74 |
| **270** | .64 | 1.06 | 97 |

**Notes/Observations:**

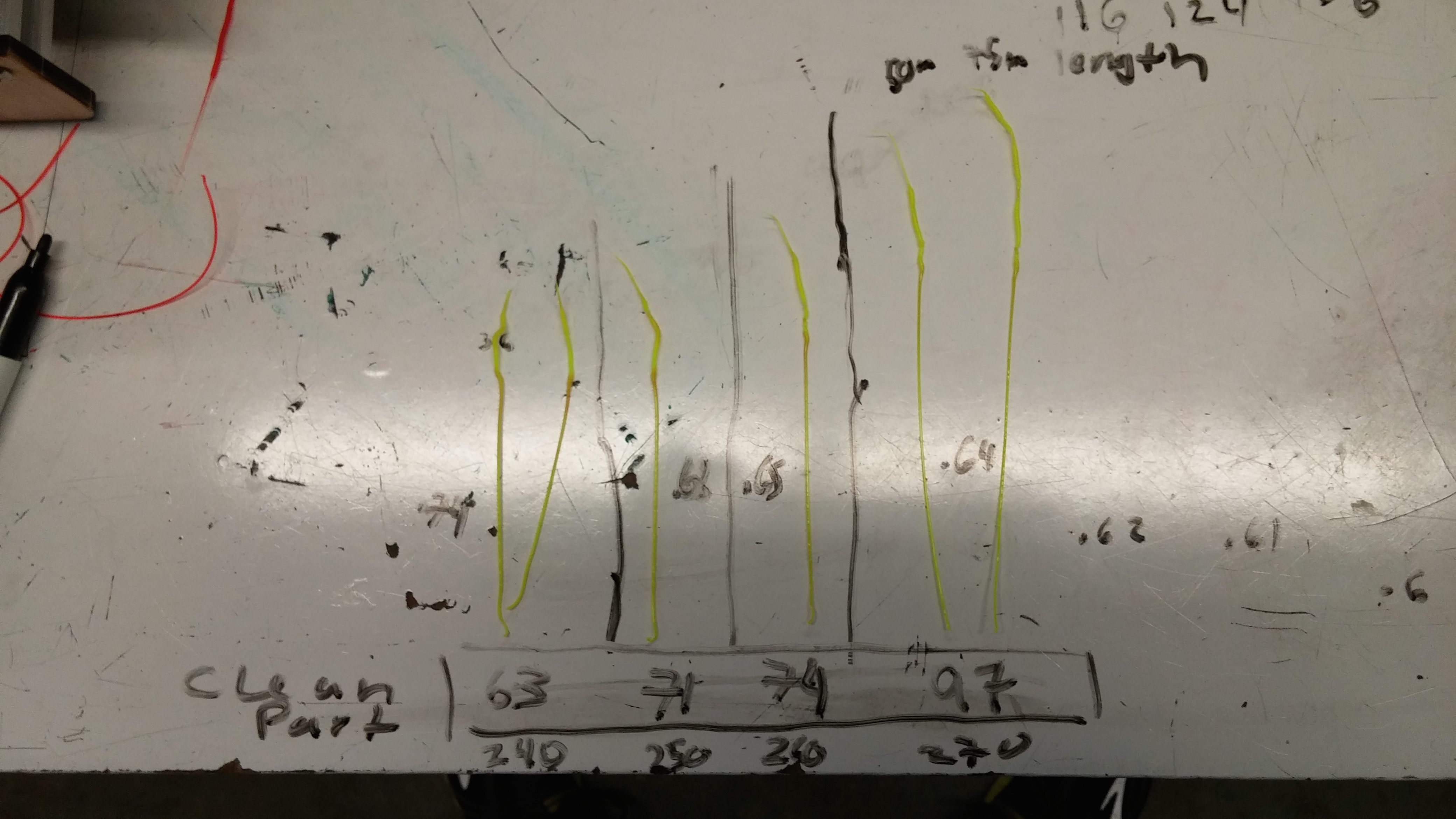
* Extruded length increases for higher temperatures and another important observation is that the area with the severe blobbing remains fairly constant in length throughout the different trials. Overall blobbing occurs at the end of each trial suggesting that even 270 degrees isn’t high enough for the given volumetric flow rate so hot end needs a higher temperature so that even if the filament is there for a shorter time it will heat up to 240.
* The initial diameter for the extruded filament for the trials decreases as the temperature increases, and it gets closer and closer to the actual orifice diameter size, this occurs because at the lower temperatures it hasn’t melted completely due to the fast speeds at which at it is travelling through the orifice so its diameter is closer to the diameter of the pulled filament which was 1.75mm, however at higher temperatures it melts properly thus it reaches the orifice diameter.

**Specifications:**

* 1.75mm Octave ABS filament
* V6 nozzle with 0.6mm orifice
* Spring Tension: (~58.70 mm for 3mm) (~58.90 mm for 1.75mm)

**Failure Mode:** Not Applicable

**Photo**



4.11 Table 11 – Pulled Filament Length at Varying Speeds

**Data**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| MELT | DRIVE | DIAMETER | ORIFICE | MATERIAL | TEMP | LENGTH |
| Volcano | Direct | 1.75 mm | 1.2 mm | ABS | 250 °C | 50 mm |

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Volume Flow Rate (mm3/min)** | **Speed**  **(mm2/min)** | **Trial 1**  **(mm)** | **Trial 2**  **(mm)** | **Trial 3**  **(mm)** | **Average**  **(mm)** |
| **200** | 83 | 49.97 | 50.01 | 49.99 | 49.99 |
| **400** | 166 | 50.04 | 49.97 | 49.98 | 50.00 |
| **600** | 249 | 49.79 | 49.81 | 49.85 | 49.82 |
| **800** | 333 | 49.68 | 49.68 | 49.71 | 49.69 |
| **1000** | 416 | 49.69 | 49.52 | 49.31 | 49.51 |
| **1200** | 499 | 49.00 | 49.23 | 48.75 | 48.99 |
| **1400** | 582 | 48.46 | 48.65 | 48.45 | 48.52 |
| **1600** | 665 | 48.57 | 48.51 | 48.39 | 48.49 |
| **1800** | 748 | 48.23 | 48.32 | 48.28 | 48.28 |
| **2000** | 832 | 46.87 | 47.21 | 47.01 | 47.03 |
| **2200** | 915 | 45.70 | 46.16 | 45.98 | 45.95 |
| **2400** | 998 | 43.73 | 42.31 | 44.69 | 43.58 |
| **2600** | 1081 | 38.58 | 35.21 | 37.64 | 37.14 |
| **2800** | 1164 | 20.13 | 18.76 | 24.04 | 20.98 |
| **3000** | X | X | X | X | X |

**Observations:**

* 2400 flow: grinding noise, 1 “click”
* 2600 flow: grinding noise, 2 clicks
* 2800 flow: grinding noise, several clicks

**Specifications:**

* Octave 1.75mm ABS Yellow
* Printrbot Alu-Extruder, direct gear drive

**Failure Mode:**  Extrusion thickening, die swell

**Analysis**

Increasing the speed at which filament is pulled by the extruder has a detrimental effect on the length of filament actually pulled. Even though the printer is set to pull 50 mm of filament in every trial, the actual length pulled dramatically drops after a certain threshold.

There are no signs of filament stripping on the hobbed gear. This means either the hobbed gear itself is slipping on the filament, but not shredding it, or the extruder motor is skipping steps due to the lack of power. This test was done with the stepper driver potentiometer allowing for maximum current to the motor. Thus this problem can be attributed to the drive/hobbed gear.

1. Analysis

5.1 Findings

The primary goal of this research was to find a set of variables that limit the material extrusion process. The variables experimented on were different sizes of filament, different materials, changes in temperature as well as motor gear ratios motor gear ratios, and the conclusions from these tests are summarized below.

Tables 2 and 5 compared ABS at both lengths of 1.75 mm and 3.00 mm while Tables 4 and 6 compared PLA at both lengths 1.75 mm and 3.00 mm. The results from these tables showed the same failure volumetric flow of 2200 millimeters cubed per second. This contradicts the hypothesis that predicted that the volumetric failure rate for 1.75 mm for both filament types would be higher than the 3.00 mm filaments due to a smaller surface area which is more conducive towards melting. The same failure volumetric flow rate could be a result of the error in the motor where after certain speed it doesn’t provide sufficient torque to pull the filament. Thus it is possible that in reality the failure rate for 1.75 mm filament is higher but it could not be ascertained in this setup due to motor failure.

The next variable tested for was the failure rate for ABS vs PLA and the data for the initial set of tests again showed the same failure rate of 2200 again probably because of the motor failure, but the later temperature tests did show a significant difference between ABS and PLA.

After all these tests, one recurring observation was that the extruded filament did show marks of threading, thus it was hypothesized that the filament was not reaching the full melting temperature due to its quick passage through the hot end leaving the marks of the hob bolt digging into it. Thus, two sets of trials were completed with increasing temperature, one measured the extruded filament length and diameter, and the second measured the pulled filament length.

As seen in tables 9 and 10 the extruded length of filament increased with increased temperature and the diameter decreased from a size greater than the orifice to just the exact size of the orifice showing a decreasing die swell ration all the way to 1. The decrease of the die swell ratio of both the PLA and ABS all the way to 1 shows that temperature is a limiting factor and that the filament really wasn’t getting hot enough as it passes through the hot end. However, one limitation to this trial was that since both the length and diameter of the extruded filament varied it was hard to compare the tests with each other since the volumes of the extruded filaments would be so different thus it was decided to run the same trial except measure the pulled filament.

The pulled filament trials obviously showed that the higher the temperature the more filament was pulled as the filament could heat up closer to its melting point hence become more viscous and then travel through with the lesser torque provided by the motor at higher speeds. The more interesting result of this trial though was the dichotomy of results between the PLA and ABS. According to tables 7 and 8, the rate of pulled filament per increase in a degree Celsius for the PLA was 1.88 but for ABS it was 3.74, almost twice as much! The reason for this is contained in section 2.25. The higher thermal conductivity for ABS and the lower specific heat capacity results in a greater change in temperature thus ABS melts more the higher the temperature increases compared to PLA thus the rate of filament pulled for ABS is 3 times higher for every degree increase in temperature.

It is often recommended that a geared extruder is used for 3.00 mm filament for the extra torque and a direct drive gear for 1.75 mm to maintain the maximum rotational speed of the motor shaft. The results confirm this idea. As seen in a few of the trials for 1.75 mm, the motor’s speed was a limiting factor. This is because the extruder was set-up on a 5:1 geared ratio. Swapping it for a direct drive gear would effectively pull filament 5 times faster. This change is demonstrated in Table 11 and the results are clearly better.

Due to possible motor error no definitive conclusions can be drawn for 1.75 mm filament compared to 3.00 filament, the data shows that they fail at about the same volumetric flow rate. However, this results of the tests do show that ABS is preferable at higher volumetric flow rates compared to PLA, and increasing the temperature will allow filament to be extruded faster.

* For each trial a certain length is extruded at a diameter as noted in the table, however after that extruded length failure occurs for every trial as motor grinding noise heard, filament gets noticeably thicker, and hardly any filament is extruded.
* Extruded length increases for higher temperatures since the increased temperature is more conducive towards the filament melting so it can escape the hot end quicker.
* In the trial at 190 degrees Celsius greatest degree die swell occurs because the diameter is .98mm which is greater than the nozzle orifice of 0.6mm, however as the temperature increases the die swell reduces as the diameter at 260 degrees is equal to the diameter of the nozzle itself.
* However, it is important to note that at the end of a certain length of the extruded filament (as seen in the picture below) die swell begins to reoccur as the diameter of the extruded filament becomes noticeably thicker. This occurs since the filament was sitting in the hot end beforehand it is sufficiently melted, however, but once the motor starts the filament near the end doesn’t spend as much time in the hot end as did the filament in the beginning thus it doesn’t get hot enough and failure as well as die swell occur.
* It is important to note that increasing the temperature did not prevent failure, just alleviated the extent of the failure as occurrence of die swell in the beginning is avoided completely at high temperatures as .6 was the cross section diameter for 260, and its occurrence later is delayed as the extruded length (before major die swell) grows steadily for each temperature.

5.2 Conclusions

All of the results of the various experiments mostly confirmed the hypothesized optimum configuration. ABS demonstrates superior melting compared to PLA, and this becomes more evident as the temperature of the hot end is increased. Filament diameter is somewhat inconclusive as early tests show that 1.75 mm fails at a lower flow rate than 3.00 mm filament. However these results are under the limitation of the motor. Once changed to a better extruder setup, the hobbed bolt became the limiting factor. It is believed that 1.75 mm is still the best, however its potential is limited by other factors.

The results yield roughly the same failure volumetric flow rate and displayed various modes of failure from severe die swell to extrusion “threading”. There is no single limiting factor that prevents shorter print times in terms of the hot end and extruder assembly. There are a variety of constraints, and these limits are different, and largely dependent on the choice of filament size.

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 10he 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.

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) |