**Hot End and Extruder Volumetric Flow**

**Analysis**

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

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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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[Jeff, Steve, Ganter, all of BLUE team]

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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. |
| **G-Code** |  |

Introduction

Purpose of Study

Motors and linear systems across the XY-plane of 3D printers are capable of very high speeds. However, maximum acceleration is vastly different from maximum printing speed. The root of this very apparent problem lies within the hot end and extruder assembly. Current hot ends and extruders are simply not able to feed, melt, and extrude material quick enough to match the maximum speed of movement.

The purpose of this study is to determine 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 that is preventing greater flow rate of material?
* Is there a dominant factor or a combination of variables that make up this limit?
* What attributes of a hot end and extrude are ideal for our goals?

Delimitations

Testing done in these experiments are purely for 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 done online. The proposed theoretical optimizations are based on conclusions found through this research. 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 constraints 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 the filament and extruding that material.

Large format speed printing yearns for a very high volumetric flow rate and it may make intuitive sense to use larger filament for these prints. 3mm will indeed deliver more volume per extruder steps given the same extruder setup. However, the feed rate is something that can be variably changed based on the 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 greater the contact surface area per unit volume of material (SA:V ratio), the greater the ability to transfer heat. This is why heat sinks seen in computers are composed of many very thin aluminum plates, because it optimizes the surface area of the aluminum while minimizing its material volume.

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

Hypothesis

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

Testing Results

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