High-Throughput Extrusion Additive Manufacturing Using Electrically Resistive Preheating

by

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Abstract

Extrusion-based additive manufacturing, commonly known as fused deposition modeling (FDM) or fused filament fabrication (FFF) is incredibly useful in industry for a variety of reasons, including rapid prototyping and the ability to create complex geometries easily. However, its further adoption is limited by relatively slow part manufacturing rates when compared to conventional manufacturing methods. Previous work has identified three modules within the FDM process which are rate limiting: speed of gantry positioning, polymer heating, and extrusion pressure. Advancements in any one module will allow for higher volumetric output, which will in turn allow for higher rates of production using FDM. This work focuses on polymer heating, and demonstrates a new concept for rapid heating of filament by introducing conductive nanoparticles into the polymer resin and resistively heating sections in flow. This technique can improve the volumetric output of FDM printers by at least 20%. First, the resistive properties of the composite filament are characterized. Second, the concept is experimentally validated by demonstrating a decrease in extrusion force required to maintain a given feed rate when using resistive heating.

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1. Introduction

Within industry, additive manufacturing has proven very useful. Certain promising applications include rapid product prototyping and the fabrication of end use tooling and molds. The main benefit additive manufacturing brings to the table is that part complexity is free. It can create geometries that are either highly impractical or completely impossible to create with conventional machining methods. However, further adoption as a means of high volume manufacturing is limited by relatively low volumetric output relative to conventional methods.

The research presented in this paper seeks to improve the printing rates of FDM 3D printers. FDM stands for Fused Deposition Modeling, in which a printer extrudes a melted thermoplastic from its nozzle. It deposits material cross section by cross section on a print bed in the XY plane, slowly building a part up from the print bed in the Z direction. Commonly used thermoplastics include ABS and PLA.

Current research (Go 2015) indicates that the feed rate of commercial FDM printers is thermally limited. The conventional method for heating the plastic is to pass the filament through a ‘liquefying chamber’ before it is extruded through the nozzle. This chamber is made of a highly thermally conductive material, typically brass, and heated to 220°C. Heat transfers to the filament from the chamber walls via conduction. However, the printer cannot heat the thermoplastic filament to melting temperature quickly relative to the speed at which it is capable of being moved. Therefore, in order to improve the printing speeds of FDM printers, the rate of filament heating must be improved.

A recent trend with 3D printing is using composite thermoplastics. That is, thermoplastics which have another material within them. Examples include carbon nanotubes, carbon fiber, graphene, and metal particulate. Benefits of these composite thermoplastics include improved structural properties, electrostatic discharge, and improved thermal conductivity. One example of these composite filaments is Blackmagic 3D, a PLA filament that is infused with Graphene. It has a measured room temperature electrical resistivity of approximately 14 ohm-mm. This gives Blackmagic 3D a unique property among composite filaments in that its resistivity is low enough to pass electrical current.

The purpose of this research is to improve the extrusion rate of FDM using a dual mode heating technique consisting of an electrically resistive volumetric preheater and a conduction liquefier as found in conventional systems. The goal is to characterize the resistive properties of the Blackmagic 3D filament, and to use this information to make a proof of concept nozzle that will demonstrate an increase in printing rate using resistive heating.

2. Background

The main goal of this work is to raise the temperature of the filament using electrical work. By modeling the filament as a closed system, we know that any change in thermal energy will be as a result of heat entering the system or the system doing work. The first law of thermodynamics states the conservation of energy as such:

\[ \Delta U = Q - W \]  

(1)
Where \( U \) is system’s internal energy, \( Q \) is heat entering the system, and \( W \) is work done by the system. A change of energy in the system can be further defined as:

\[
\Delta U = mc_p(T_2 - T_1)
\]

(2)

Where \( m \) [kg] is the mass of the closed system, \( c_p \) is the specific heat of the material within the system, and \( T \) is the temperature of the system. By combining Equations 1 and 2, and considering that we only wish to heat the closed system with work \((Q = 0)\), the expression becomes:

\[
W = mc_p(T_2 - T_1)
\]

(3)

Electrical power is defined as:

\[
P = IV = I^2R = \frac{V^2}{R}
\]

(4)

Where \( I \) is electrical current, \( V \) is electrical voltage, and \( R \) is electrical resistance.

Work is defined as the integral of power:

\[
W = \int_0^t P \, dt = Pt
\]

(5)

Where \( P \) is power and \( t \) is time.

Upon combining Equations 3, 4, and 5, the following expression is produced:

\[
\frac{V^2}{R} t = mc_p(T_2 - T_1)
\]

(6)

Equation 6 expresses the change in temperature of a closed system of mass \( m \), specific heat \( c_p \), and resistance \( R \) when subjected to an electrical voltage \( V \) for an amount of time \( t \). Voltage, mass, and time are all variables that can be controlled. The specific heat for PLA is already well documented, and the change in temperature is what is being induced. The last variable to understand is the system’s resistance.

Resistance is geometry dependent, and defined as:

\[
R = \rho \frac{l}{A}
\]

(7)

Where \( \rho \) is electrical resistivity (a material property), \( l \) is the length of the material, and \( A \) is the cross sectional area of the material.

Equation 7 will be used to normalize resistance measurements of filament to the size of the filament. Once the resistance is known for a piece of filament, its change in temperature when subjected to an electrical current can be predicted using Equation 6.
3. Material Characterization

3.1 Introduction

To evaluate the effectiveness of resistive heating of Blackmagic 3D, the resistive properties of the filament must first be understood. The manufacturer listed only a single resistivity at an unspecified temperature for the filament. This work finds that resistivity is temperature dependent, and that resistivity varies over an order of magnitude from room temperature to the operating temperature of FDM machines. Having a more accurate understanding of this property will allow for more accurate predictions of temperature increase when subjected to a resistive preheat. This data will also create a benchmark of composite filament resistivity/performance. If, in the future, more composite filaments are evaluated for a resistive preheat application, they can be quantitatively compared to Blackmagic 3D.

3.2 Experimental Setup

In this experiment, the resistivity of graphene infused PLA was measured at various temperatures between 30°C and 230°C. The following assumptions were made: the sample had a constant cross sectional area, the sample had a uniform temperature profile when the resistance was measured, and the electrical leads had good electrical contact.

This experiment used a machined block of aluminum to act as a heat sink. A thick walled alumina tube was press fit into the aluminum block. Its internal diameter was 1.75mm, and allowed for a slip fit of the Blackmagic 3D filament. The alumina tube provided good thermal conduction between the aluminum and the filament, but electrically isolated them so that resistance measurements could be taken.

Two ‘caps’ were machined out of PEEK, a thermoplastic that has useful operating temperatures up to 250°C. These round caps were concentric with the alumina tube, and fit into the aluminum block as well. These ‘caps’ had threaded holes at their centers. Machine screws threaded into these holes, and the screws were tapered to a point at their ends. The pointed tips of the screws were also a slip fit within the alumina tube, and the distance they penetrated could be adjusted by screwing them into or out of the peek caps. Thus, the two screws could contact the filament on either side, and the pressure they exerted on the filament could be varied. The tapered points allowed for good electrical contact between the screws and the filament. By attaching a digital multimeter to the screws, the resistance of the filament could be measured.
This experiment used an omega temperature controller (CNi3244-C24), an Omega solid state relay (SSRDC100VDC20), a ‘k-grade’ thermocouple, a 12V output power supply, and one 12V 40W Signstek cartridge heater (SW043) to control the aluminum heat sink’s temperature.
3.3 Experimental Procedure

During the experiment, the omega temp controller was set to 230°C. At 5-degree intervals, the temperature and resistance readouts were manually recorded using Excel. Before the experiment the length of the sample is measured using calipers. Resistivity is calculated using Equation 7 and then plotted against temperature in excel to produce a graph.

Between experiments, the heat sink was quenched in water and dried off. Filament was removed from the alumina tube (usually with a drill press), and then the experiment was run again. All data shown in Section 3.4 was collected in one setting such that ambient conditions were consistent between trials.

3.4 Results

Recorded data for electrical resistivity as a function of temperature had a fairly large amount of variability. However, while the resistance values for a given temperature vary greatly, their overall shapes with respect to temperature are very similar. Measurements were recorded from room temperature to 230°C, but 220°C is the usual operating temperature of FDM printers using PLA.

![Resistivity Profiles Blackmagic 3D](image)

Figure 3: Resistivity profile of Blackmagic 3D with respect to temperature. The data is from 7 tests out of 10 total conducted.
The above graph shows the electrical resistivity profile with respect to temperature for Blackmagic 3D. While the resistivity values for a given temperatures vary greatly, the general shape does not. Two peaks in resistivity tend to be present, one at 90°C and a second at 180°C.

The graph includes results from 7 out of 10 tests conducted. The data sets not included were deemed outliers. Outlier 1 had only a single peak resistivity at 90°C, and its peak value was an order of magnitude greater than any of the rest. Outlier 2 had a peak resistivity 6 times greater than Test 5, and sporadic resistivity values between 90°C and 180°C. Outlier 3 only had a peak resistivity at 90°C, and its peak value was half the value of Test 7’s 90°C peak. Because each of these outliers exhibited a unique trait that only occurred 10% of the time, and because the deviated substantially from Tests 1-7, they were deemed erroneous and excluded from Figure 3.

**Blackmagic 3D Filament Average Resistivity Profile**

![Graph showing resistivity profile](image)

*Figure 4: Average resistivity as a function of temperature for Blackmagic 3D PLA filament. Values calculated from data shown in Figure 3 with a 95% confidence interval.*

Figure 4 shows the average resistivity, calculated using data from Figure 3. Its shape is consistent with Tests 1-7, with two peaks at 90°C and 180°C, and an intermediate trough.

A Matlab script was written to predict the temperature of filament over time. It used the recorded resistivity data from figure 3, specific heat data (“PLA” 2016), and Equation 6. It took as inputs voltage, time, and mass. Using an iterative loop, temperature could be calculated at each time step, and then plotted.
This graph shows temperature over time when a filament 12.7 mm long is subjected to various voltages. Temperature increase is proportional to the square of voltage (Equation 6).

The rate of temperature change corresponds very well to the resistivity range in Figure 3. As the resistivity increases, the power put into the system decreases (Equation 4). Thus, when the filament is at a temperature that corresponds to high resistivity, temperature change is slow. At temperature ranges with low resistivity, the heating rate increases dramatically, most evident in the plot of 24V.

It should be noted that this model is for stationary filament. However, in a 3D printer the filament is moving at a constant velocity as it slides along the contacts. In the stationary model (Equation 6), temperature is constant along the length of the filament. Since resistivity is temperature dependent, resistivity is also constant along the length of the filament. However, in the sliding case, different parts of the filament have been exposed to current for different amounts of time. Therefore, there is a temperature and resistivity gradient along the length of the filament. While this is not accounted for in the above model, the model is likely still indicative of general trends with changes in voltage, as well as approximate times to heat to a given temperature.

An accurate mathematical model of the sliding case would require a much more rigorous mathematical approach, taking into account the length-wise temperature/resistivity gradient.
3.5 Discussion

It is unknown why the resistivity peaks at 90°C and 180°C. It is possible that they correlate to the glass transition and melting temperatures of PLA, which are 55°C and 175°C respectively (Garlotta 2001).

The discrepancy between 55°C glass transition temperature and the recorded 90°C peak is obvious. However, this is likely due to how the experiment was conducted. In the experiment, temperature was measured at the surface of the aluminum heat sink. Temperature was recorded at 5-degree intervals, but not allowed to reach steady state for each interval. This was done for each trial, so it does not affect the results of each test relative to one another. However, it is highly likely that there was a thermal gradient between the surface of the aluminum heat sink and the filament. This phenomenon would be even more pronounced at lower temperatures, where the block would heat very quickly, but not have substantial time to transfer heat into the filament. Thus, it is conceivable that the surface of the aluminum heat sink was 90°C when the filament itself was only 55°C due to this ‘thermal lag’. While this cannot definitively confirm that the first peak is due to the material being at its glass transition temperature, it leaves it open as a possibility for future research to explore.

As the temperature of the block increases, the rate at which its temperature changes decreases, and the thermal lag is lessened. As the aluminum heat sink gets close to 180°C, it’s possible that the thermal lag is only 5°C, and the filament is at a temperature of 175°C.

The suggestion that the changes in resistivity could be correlated to phase transitions is supported by (Zheng et al. 2011). The paper shows a strong correlation between phase transitions and changes in electrical resistance in crystalline materials, and suggests that changes in electrical resistivity at phase transition temperatures are due to internal stresses changing electrical contact resistances. PLA is at least partially crystalline, but its degree of crystallinity varies based on many considerations (Battegazzore 2011). Further research would be required to evaluate the validity of the hypothesis that the resistivity changes are due to phase transitions for Blackmagic 3D.

It is also unknown why the resistivity varies so greatly between different lengths of filament, but it is likely due to a lack of homogeneity in the composition of PLA and graphene particles. Variable graphene density along the length of the filament, as well as variable particulate size could both contribute to this phenomenon. As it relates to the above discussion of phase transitions, it is also possible that the inclusion of graphene particulate could shift some of the phase transition temperatures of the filament relative to pure PLA. Variable sizes of particulate could also cause different internal stresses during phase transitions, leading to variable electrical contact resistances within the material.

4. Custom Nozzle - V1

4.1 Introduction

A custom nozzle was made to use the electrically conductive properties of the Blackmagic 3D PLA filament as a resistive pre-heating mechanism. Its main function is to allow the filament to be heated using resistive heating and conduction in parallel.

Most conventional FDM machines use a pinch wheel mechanism to drive the filament through the liquefying chamber. It consists of a stepper motor driven knurl wheel, and a smooth
spring-loaded wheel to apply a normal force. The resistive force the liquefying chamber applies to the filament limits the filament feed rate. If the drive assembly reaches a critical force, the knurl wheel shears the filament and ceases to have mechanical purchase with which to extrude filament. Therefore, if the force required to extrude filament can be reduced, the feed rate can necessarily be increased, improving volumetric throughput (Go 2015).

In this experiment, the nozzle was used both with and without the electrical pre-heat, and its performance was evaluated by examining the force required to extrude filament at a given extrusion rate. The hypothesis was that the electrical preheat would lower the force required to extrude material, since it would heat the filament to an extrude-able temperature more quickly.

4.2 Experimental Setup

This setup was comprised of a Printrbot servo motor and knurl wheel assembly, a load cell, a custom resistive heating adapter, and a standard conduction nozzle, all in series. The motor, cartridge heater, and thermistor were controlled with a Rambo board that interfaced with Repetier software, and the load cell data was captured using an Arduino board.
4.2.1 Drive Assembly

The drive assembly was bought stock from Printrbot. It consists of a servomotor driven knurl wheel and a pinch wheel mechanism. The pinch wheel applies a normal force to the filament, which pushes it into the knurl wheel. This gives the knurl wheel mechanical purchase on the filament and allows it to drive the filament through the rest of the assembly.
The drive assembly can fail in two ways. The first is that the filament can buckle if it is pushed through an unsupported length. The other method of failure is when the motor applies a drive force that exceeds the maximum shear stress of the filament. In cases such as this, the knurl wheel cuts out part of the filament, with the shape matching the curvature of the knurl wheel. This occurs when the motor is trying to push the filament through the extrusion assembly faster than the filament can move.

4.2.2 Load Cell

The load cell connects the drive assembly and the extruder. It measures the total force the motor exerts to move filament at a given feed rate.

4.2.3 Custom Resistive Heating Adapter

The ‘Custom Resistive Heating Adapter’ (from now on: Adapter) was made using a Stratasys Mojo 3D FDM printer. It has a 1.75mm through hole along its main axis, which the filament travels through. Perpendicular to this hole is housing for a compression spring. Lastly, there is a clamp mechanism to attach the part to the standard conduction nozzle.

Figure 7: Cross sectional view of spring housing. The filament is fed through a compression spring which maintains constant physical contact with the filament. By attaching a wire to the spring, a good electrical contact can be established.

This part applies an electrical current to the filament by using a compression spring, similar to one found in a ballpoint pen. The filament is slightly wider than the distance between the coils, and must stretch wider as the filament slides through it; this provides consistent contact between the spring and the filament body. A wire is attached to the spring which connects to an external power supply.
4.2.4 Standard Conduction Nozzle

The 'Standard Conduction Nozzle' (from now on: Nozzle) consists of a peek sheath, a Teflon tube, a threaded steel tube, an aluminum heat sink, and brass nozzle. Both the nozzle and the threaded tube are screwed into the aluminum heat sink, and are co-axial.

![Diagram of the Standard Conduction Nozzle](image)

The PEEK sheath has female threads and is screwed onto the exposed end of the threaded steel tube. When assembled, a wire is clamped between the threads with a nut to establish an electrical connection. Without filament, the PEEK sheath and Teflon tube are a non-conductive bridge between the adapter and the nozzle. However, when the filament is inside the overall assembly, it completes the circuit. Current can then be applied to preheat the filament.

The heat sink also has standard housing for a cartridge heater and thermistor for temperature control.

4.3 Experimental Procedure

In this experiment, the nozzle temperature was set to 220°C. When the Arduino began recording load cell data, the motor was instructed to extrude 10 cm of filament at a specified rate. Rates used were 2, 4, and 6 mm/s. A baseline data capture was done for each of these speeds.
without any resistive heating. The process was then repeated with resistive heating. A constant 12V input was applied to the leads using a BK Precision 1550 power supply.

4.4 Results

Figure 8 shows force plotted against time, both with and without a 12V preheat. Both sets of data were recorded at an extrusion rate of 2mm/s.

![Extrusion Force](image)

**Figure 9: Force exerted by motor at 2mm/s extrusion rate. Both preheat and no preheat data sets are shown. Filament failure is indicated by oscillation in 12V preheat data.**

Results were not as expected. The extrusion assembly performed much better without the 12V preheat. The blue data set shows the extrusion force over time without the 12V preheat, and the red data set shows the extrusion force with the 12V preheat.

No preheat showed an initial peak force of approximately 24N, and a second peak extrusion force of 35N, after which the force steadily decays.

The preheat showed an initial peak force of approximately 25.5N, and a second peak force of 43.5N, after which the knurl-wheel and filament interface mechanically failed. The oscillation of force in the graph represents the knurl wheel attempting to grab at the filament and continue pushing it, but only getting minimal purchase.

A further distinction between the two graphs is shown in the portion between the peak forces. The 12V preheat shows a more volatile increase to its peak, whereas no preheat has a
relatively smooth increase. The oscillation could indicate a slip-stick condition on the inside of the nozzle as the filament melts.

Data was also recorded for 2, 4, and 6 mm/s extrusion rates without a preheat, but only at 2 mm/s with a preheat since it caused a failure.

It was determined that it would be best to pursue an alternative design prior to running more tests (see discussion).

4.5 Discussion

The filament failed because the nozzle assembly required more force for extrusion than the motor could apply before reaching the filament yield stress. Upon disassembling the setup, it was revealed that the filament was stuck in the space below the spring. It had to be drilled out in order for the resistive heater to be functional again. The filament that had made it past the spring had much less visible marks from the knurl wheel, indicating that it had risen to at least a glass transition temperature.

Two potential reasons for this were identified. 1) There is a short unsupported length beneath the spring contact. It was created to more easily feed filament through the hole. It is possible that the filament softens right below the spring, and instead of being pushed down into the Teflon tube, it expands and clogs the hole. This is consistent with the observation in which the filament was stuck right beneath the spring. 2) The distance between leads was large. Assuming part of the filament reached its glass transition temperature before reaching the end of the resistive length, it would become viscous and have a no-slip boundary condition along the wall of the Teflon tube. This would create a large area with frictional forces that would otherwise not be present without the 12V preheat.
It is difficult to tell whether the problem solely reason 1, both 1 & 2, or if 2 causes 1. In either case, a new resistive heater was developed which removed any unsupported space, and also shortened the length over which the 12V is applied.

A new Adapter was created to address these issues. It would reduce the distance between leads, as well as eliminate any unsupported length of filament.

5. Custom Nozzle – V2

5.1 Introduction

The adapter was redesigned to address the two main design criteria that were thought to limit the functionality of the adapter (see Section 4.5 discussion). These modifications removed any unsupported length beneath the spring contact, as well as a reduction in distance between electrical leads. This experiment had identical procedure to that of Section 4.

Once again, the goal is to show that using resistive preheating reduces the force required to extrude filament at a given rate.

5.2 Experimental Setup

This setup was comprised of a Printrbot servo and knurl wheel assembly, a load cell, a custom resistive heating adapter, and a standard conduction nozzle, all in series. The motor, cartridge heater, and thermistor were controlled with a Rambo board that interfaced with Repetier software, and the load cell data was captured using an Arduino board.

Please see the Sections 4.2.1 & 4.2.2 for details on the drive assembly and load cell.
5.2.1 Custom Resistive Heating Adapter & Standard Conduction Nozzle

As discussed in the previous section, the main changes to the assembly that needed to be made were eliminating the unsupported length below the compression spring and reducing the distance between the leads.
The above cross sectional view of the V2 Adapter shows the removal of the unsupported length of filament, as well as a shorter distance between the electrical leads.

The experimental procedure used was the same as described in Section 4.3.

5.4 Results

Load cell data was not relevant for this experiment. While attempting to extrude filament without an electrical preheat, the filament would expand into the spring housing and jam.
The reason that this happened is that while the experiment was being prepped, heat would travel up the filament from the heat sink. The portion within the spring housing would reach a temperate at which it became malleable. Due to this, during extrusion the filament would buckle and experience Poisson expansion. Since the filament reached a buckling heat so quickly, it wasn’t possible to prep the experiment before a buckling temperature was reached. Due to this, no further experiments could be run with this setup.

5.5 Discussion

Heat rapidly traveling up the filament indicates a very high thermal conductivity in the filament. While it is unfortunate that this experiment was unable to collect data, learning of this material characteristic was very useful. The reason that a compression spring was used as an electrical contact was because it would always be physically touching the filament. There was worry that the filament would not have a consistent enough contact if it were sliding co-axially inside a second steel tube. However, we now know that if the filament has its temperature increased, it will undergo a Poisson expansion with minimal axial compression force. This can be used to make sure that it has good contact within an electrically conductive tube, if the tube can also be heated.

This finding led to a third design, in which two co-axial brass tubes are electrically isolated by an intermediate Teflon tube. By removing the compression spring contact, the filament is no longer afforded the opportunity to expand into the spring housing.
6. Custom Nozzle – V3

6.1 Introduction

This experiment had the same testing procedure as the previous two. The force required to extrude filament at a given feed rate was recorded at various voltage inputs, and used to determine if resistive heating allowed for a substantial increase in extrusion output. However, the nozzle design deviated substantially from the two previous designs. It did not rely on a compression spring for constant contact for an electrical lead. Instead, it used two co-axial brass tubes as electrical leads, electrically isolated from each other with a Teflon tube.

6.2 Experimental Setup

This setup was comprised of a Printrbot servo and knurl wheel assembly, a load cell, a custom resistive heating nozzle, all in series. The motor, cartridge heater, and thermistor were controlled with a Rambo board that interfaced with Repetier software, and the load cell data was captured using an Arduino board.

Please see Sections 4.2.1 & 4.2.2 for details on the drive assembly and load cell.

Figure 14: Extrusion Force Test - From top to bottom: drive mechanism, load cell, resistive heating adapter (with + lead), standard conduction nozzle (with - lead).
6.2.1 Resistive Heating in Parallel with Standard Conduction Nozzle

As discussed in the previous section, a compression spring could no longer be used due to the filament’s expansion into its housing chamber. To replace it, the filament was fed through a brass tube. Two nuts were threaded onto the brass tube, with a wire sandwiched between them.

![Diagram of V3 Nozzle](image)

**Figure 15: Cross sectional view of V3 Nozzle. Two brass tubes are used as electrical leads, with a distance of 12.7 millimeters between them.**

The above cross sectional view depicts the path of the filament through the V3 nozzle, and how it completes the circuit between the two brass tubes in order for resistive heating to occur.
6.3 Experimental Procedure

In this experiment, the nozzle temperature was set to 220°C. When the Arduino began recording load cell data, the motor was instructed to extrude for 10 seconds at a specified rate. Rates used were ranged from 25 to 80 mm/s at 5 mm/s intervals. Applied voltages ranged from 0 to 24 V at 6V intervals, using a BK Precision 1550 power supply. The experiment was first ran using a 400 micrometer diameter nozzle tip, which is standard for FDM 3D printers. The procedure was then repeated with the nozzle tip diameter increased to 1 millimeter.

![Graph](image)

**Figure 16:** This graph shows data captured by the load cell with an extrusion rate of 40 [mm/s]. The voltages applied for preheat were 12V, 18V, and 24V. The peak of the 12V data series indicates a maximum force of 63N, at which point the filament fails.

The above graph shows an example of what the data captured by the load cell looks like. In this particular case, it was at a feed rate of 40 mm/s, with 3 separate voltages applied. The peak force of the 12V data series, followed by a sharp decay, indicates a mechanical failure in the filament. This occurs when there is too much resistance to the filament, and the force applied by the knurl wheel cuts away filament material rather than propel it through the nozzle.

In Section 6.4, the average values are calculated taking the average force from 2 seconds to 10 seconds of load cell data.
6.4 Results

Results from this experiment confirm the hypotheses that using a resistive preheat can help increase the maximum extrusion rate of FDM printers. For a given extrusion speed, there is a very noticeable trend between an increase in applied voltage and a decrease in force required to extrude filament. Thus, the filament can be extruded at a greater rate while still remaining below the filament failure force.

The fastest rate achieved without resistive preheat for the 400 micrometer diameter nozzle was 32 mm/s. The fastest speed recorded with a resistive preheat using 24V was 40mm/s. This is a 20% increase in feed rate.

The fastest rate achieved without resistive preheat for the 1 millimeter diameter nozzle was 50 mm/s. The fastest speed recorded with a resistive preheat using 24V was 80mm/s. This is a 32.5% increase in feed rate.

Table 1: Average extrusion force [N] required to maintain a constant feed rate at various voltages [V]. F indicates a failure, and X indicates that there was not a test conducted. This data was collected using a 400 micrometer diameter nozzle tip. Error computed with 95% confidence interval.

<table>
<thead>
<tr>
<th>Velocity (mm/s)</th>
<th>0V</th>
<th>6V</th>
<th>12V</th>
<th>18V</th>
<th>24V</th>
</tr>
</thead>
<tbody>
<tr>
<td>25mm/s</td>
<td>32.2 ± 0.4 N</td>
<td>33.5 ± 0.4 N</td>
<td>23.2 ± 0.3 N</td>
<td>22.6 ± 0.4 N</td>
<td>22.1 ± 0.4 N</td>
</tr>
<tr>
<td>30mm/s</td>
<td>43.4 ± 0.9 N</td>
<td>34.8 ± 0.4 N</td>
<td>30.4 ± 0.5 N</td>
<td>26.0 ± 0.4 N</td>
<td>30.6 ± 0.4 N</td>
</tr>
<tr>
<td>35mm/s</td>
<td>F</td>
<td>40.0 ± 1.0 N</td>
<td>39.8 ± 1.3 N</td>
<td>41.8 ± 1.4 N</td>
<td>32.1 ± 0.8 N</td>
</tr>
<tr>
<td>40mm/s</td>
<td>X</td>
<td>X</td>
<td>F</td>
<td>44.0 ± 5.1 N</td>
<td>35.1 ± 0.7 N</td>
</tr>
</tbody>
</table>

Table 2: Average extrusion force [N] required to maintain a constant feed rate at various voltages [V]. F indicates a failure, and X indicates that there was not a test conducted. * indicates that the filament failed right at the end of the data capture. This data was collected using a 1 millimeter diameter nozzle tip. Error computed with 95% confidence interval.

<table>
<thead>
<tr>
<th>Velocity (mm/s)</th>
<th>0V</th>
<th>6V</th>
<th>12V</th>
<th>18V</th>
<th>24V</th>
</tr>
</thead>
<tbody>
<tr>
<td>50mm/s</td>
<td>36.6 ± 1.1 N</td>
<td>34.2 ± 0.9 N</td>
<td>29.5 ± 0.6 N</td>
<td>25.7 ± 0.4 N</td>
<td>21.0 ± 0.2 N</td>
</tr>
<tr>
<td>55mm/s</td>
<td>F</td>
<td>33.7 ± 2.5 N</td>
<td>39.2 ± 1.0 N</td>
<td>35.8 ± 1.1 N</td>
<td>24.8 ± 0.4 N</td>
</tr>
<tr>
<td>60mm/s</td>
<td>X</td>
<td>43.7 ± 1.1 N</td>
<td>45.3 ± 0.9 N</td>
<td>38.6 ± 1.2 N</td>
<td>26.6 ± 0.5 N</td>
</tr>
<tr>
<td>65mm/s</td>
<td>X</td>
<td>F</td>
<td>50.7 ± 1.2 N*</td>
<td>37.3 ± 0.9 N</td>
<td>30.3 ± 0.6 N</td>
</tr>
<tr>
<td>70mm/s</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>F</td>
<td>34.8 ± 0.5 N</td>
</tr>
<tr>
<td>75mm/s</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>37.5 ± 0.6 N</td>
</tr>
<tr>
<td>80mm/s</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>45.1 ± 1.0 N</td>
</tr>
<tr>
<td>85mm/s</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>F</td>
</tr>
</tbody>
</table>

As would be expected, the above chart shows that for an increase in speed at a given voltage, there is an increase in the average force required to extrude the filament at that speed.

At a given speed, as the voltage increases there is a downward trend in force required to maintain a constant feed rate.
Extrusion Force Vs. Feed Rate
400 Micrometer Nozzle
Volumetric Output [mm$^3$/s]

Figure 17: Extrusion force plotted against feed rate is compared between many voltages. Overall, this graph shows that an increase in voltage causes a decrease in extrusion force for a given feed rate. Error bars omitted for clarity.

Extrusion Force Vs. Feed Rate
1mm Nozzle
Volumetric Output [mm$^3$/s]

Figure 18: Extrusion force plotted against feed rate is compared between many voltages. Overall, this graph shows that an increase in voltage causes a decrease in extrusion force for a given feed rate. Error bars omitted for clarity.
In the above graphs, each line represents a constant voltage. The downward shift between each line shows that for a given feed rate, increasing the voltage decreases the extrusion force. Theoretically, none of the lines should intersect, since that would indicate that an increase in voltage doesn’t always correlate to a decrease in extrusion force. Possibilities for this occurring will be discussed in the next section. However, looking at the extremes of 0V and 24V, we still see that the trend of an increase in voltage causing a decrease in extrusion force holds true.

**Figure 19**: Extrusion force vs. Voltage is compared for several feed rates. The trend lines show that as voltage is increased, force required to extrude at a given feed rate is decreased. Error bars omitted for clarity.
Figure 20: Extrusion force vs. Voltage is compared for several feed rates. The trend lines show that as voltage is increased, force required to extrude at a given feed rate is decreased. Note – Data for 70, 75, and 80 mm/s extrusion rates were excluded since there was not enough data to form a line. Error bars omitted for clarity.

The same data is shown in the above graphs, but with different axes. It shows that for a given feed rate, increasing the voltage decreases the extrusion force. The negative slope of the trend lines indicates this. Similar to Figures 16 & 17, the slope between each data point on a series should theoretically always be negative. While this is not always the case between local points, the global trend is still very convincing. Possibilities for why there are local positive slopes will be discussed in the next section.

6.5 Discussion

Overall, the trend lines in Figures 19 & 20 support the hypothesis that increasing the resistive heating voltage lowers the force necessary to extrude filament at a constant feed rate. The main inconsistency with this finding is that this correlation isn’t always the case from data point to data point.

The most likely cause for this is the inconsistency from data point to data point is the inherent inconsistency in the resistivity of the filament itself. This inconsistency is shown in Figures 3 & 4. While ideally all variables but one are being held constant, the variability of the filament resistivity can never truly be pinned down. The only way to determine a more accurate correlation between voltage and extrusion force is to record and average much more data. After doing so, the results will come to a probabilistic equilibrium, and results will be less likely to be skewed by outlier resistivities.
7. Future Work

7.1 Material Characterization

One proposed hypothesis for why the filament had high variability in its resistivity was that production of the filament did not allow for complete homogeneity of graphene particles and PLA. It was proposed that variable percentage compositions of PLA vs. graphene might be the cause behind this phenomenon. It would be interesting to know a rough percentage composition of the filament in conjunction with its resistivity profile. If we can then see a correlation between the amount of graphene in a filament sample and its resistivity values, we may be able to conclude that poor process controls during manufacturing are the reason for high resistivity variability.

I would propose measuring the density of a filament sample prior to running the experiment described in Section 3. By comparing it to the density of pure PLA, the relative percent composition of graphene can be estimated. By comparing approximate percentage composition of PLA and the resistivity profile, one might be able to draw conclusions about the effects of variable graphene percentage compositions on resistivity. Between tests, if the weight of specimens does not change much, but the resistivity does, that might mean that particle size is what causes variable resistivity, not percent composition.

Another unresolved point was discussed in Section 3.6, in which I described a ‘thermal lag’. This thermal lag was the byproduct of the heat gradient between the surface of the heat block (where temperature was measured) and the filament. In order to determine if the resistivity peak was due to a glass transition temperature phase change, a better measurement of the temperature at which the first resistivity peak occurs would be necessary. In order to accomplish this, the temperature of the filament would have to be raised at 5 degree increments and be allowed to come to thermal equilibrium.

7.2 Resistive Preheat Experiment

The main complication with the experiment described in Section 6 is that it is difficult to isolate only one variable. This is because the resistivity of the filament is constantly in flux. In order to minimize the effect of this variability on results, much more data must be taken at each speed and voltage combination. Data should also be recorded at even greater voltages to see if there is a limit at which resistive preheating is no longer efficient.

Testing multiple lengths between leads would also be interesting. As you decrease the length, you decrease the resistance of the filament. However, you also reduce the time the filament length spends under electrical current. It is unknown whether changing the length would have an effect or not.

If the nozzle’s components could be better thermally isolated, this would be ideal as well. As experiments progress, the whole nozzle starts to heat up, which could affect the results. By either using materials with better thermal properties, or by implementing some sort of cooling system, the temperature of the nozzle components could be considered constant across tests.

It would also be interesting to gather data for multiple nozzle tip diameters as well. While it is trivial that an increase in nozzle tip diameter will lead to a decrease in force required to extrude, having data to quantify that decrease would be very interesting.
7.3 Resistive Preheat Design

This nozzle was designed for the purposes of testing the viability of an electrically resistive preheat. While it did that well, it would not be viable in a high performance 3D printer. If future work leads to testing the concept in a functioning 3D printer, the design would have to be consolidated into a lighter version. The nozzle would need to be lighter so that it would have less inertia when being moved by the 3D printer gantry. This would lead to an increase in accuracy, as well as a reduction in power required to move the print head.

Currently, it is difficult to keep every hole in alignment. Creating a design that lends itself to being made with better tolerances would help greatly, as it would reduce internal sliding resistances. Furthermore, the Teflon used in the V3 nozzle was very soft. If it was compressed at all as the nozzle was assembled, its inner diameter decreases. Using a stiffer grade would keep its inner diameter more consistent between assemblies.

Lastly, if the nozzle could be made with materials with lower sliding resistances that still had the correct electrically conductive properties, that would also improve its performance.

8. References