Solid Freeform Fabrication 2017: Proceedings of the 28th Annual International
Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference
Reviewed Paper

Exploring the Manufacturability and Resistivity of Conductive Filament Used in Material Extrusion Additive Manufacturing

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ABSTRACT

Additive manufacturing (AM) has the unique ability to build multifunctional parts with embedded electronics without the need for post-print assembly. However, many existing forms of multifunctional AM are not easily accessible to hobby-level users. Most hobby-level desktop 3D printers are only used with non-conductive filaments. Recently however, conductive filaments have become increasingly available for material extrusion desktop printers. Ideally, the use of these filaments would allow circuitry to be printed simultaneously with the rest of the structure, enabling complex, inexpensive, multifunctional structures. However, the resistivity of conductive filament is significantly impacted by the geometry of the print and the printing parameters used in the build process. In this study, two types of commercially-available conductive filament were tested under a variety of parameters. It was found that print temperature, layer height, and orientation all significantly affect the resistivity in various ways. The knowledge from this research will allow users to design better multifunctional parts that have reduced resistivity.

1. INTRODUCTION

Additive Manufacturing (AM, or 3D printing), is a process that forms complex three-dimensional parts by building layer by layer. Compared to traditional subtractive manufacturing processes, AM offers many unique advantages. With AM, complex geometries can be produced quickly with low tooling costs, reduced lead times, and rapid iteration [1]. The material extrusion process is one of the most popular and inexpensive form of AM. In this process, thermoplastic material is heated until it is past its melting point and then deposited onto a build platform. A fine nozzle is used to direct the deposition of material and a robotic structure controls the position of the nozzle to create the desired geometry [2]. Material extrusion is simple, easy to learn, and highly accessible, making it popular among both hobbyists and industrial manufacturers.

The layer-wise nature of AM allows abundant flexibility in the design process, including access to the entire internal structure of a design as it is being manufactured. This makes it possible to embed foreign components within the internal structure and then continue to print over them. By building components directly into the structure, the final product can be manufactured without the need to assemble, fasten, or glue anything afterwards. The ability to embed components leads to multifunctionality, where fully functional products are created by embedding different foreign components (particularly electronics) within the print. Ideally, this would greatly shorten or even eliminate the time needed to assemble the product afterwards, speeding up production and reducing potential points of failure. However, many existing forms of printed electronics require expensive equipment and special inks, putting them out of reach for a large group of users.

Recently however, carbon-based conductive filaments have been developed for use in desktop-scale material extrusion printers. The resistivity of these filaments have been measured by researchers under ideal circumstances [3], [4]. However, the material extrusion process can be used with a wide range of parameters and geometries, which may impact resistivity beyond what has been measured. For example, resistivity is usually measured based on a solid, homogeneous block of material, which is not what actually would be used in a multifunctional part. Existing research has not looked at the effect of factors such as nozzle temperature, layer height, geometry, or orientation on the resistivity of these conductive filaments. In addition, the effect of encasing conductive filament with non-conductive filament (as in an embedded component) has not been studied. This is important since multifunctional parts commonly make use of embedded filaments, and it is necessary to ensure that embedding does not increase resistivity of conductive traces.

In this research study, two different types of conductive filament, Protopasta conductive PLA and BlackMagic conductive graphene, are tested under different printing parameters and geometries to evaluate their resistivity and manufacturability. In addition, the effect of embedding (via a dual-extrusion process) on resistivity is evaluated. Taking what is learned from the experimentation, the end goal is to determine guidelines that can allow potential users to better design for additive manufacturing when using conductive filaments.

2. EXISTING RESEARCH OF MULTIFUNCTIONAL ELECTRONICS IN AM

Related research has been divided into three sections. Section 2.1 discusses the possibilities of multifunctional printing. Section 2.2 discusses direct write technology with conductive materials. Section 2.3 discusses recent studies into material extrusion conductive filaments.

2.1 Multifunctional AM

Since its introduction, AM has offered many advantages in the way components can be designed and made. The freedom of design for additive manufacturing (DfAM) and the availability of an ever-expanding library of materials has led to the growth of multifunctional AM. While standard AM uses just one material, the idea behind multifunctional printing is combining different types of materials - particularly electronics - so that functional components can be produced without the need to assemble any parts after the build process. Some recent work has explored the use of AM with conductive materials to see what can be done with current technology.

Aguilera et al. [5] designed and built a printed electric motor, taking advantage of the embedding capability of AM. Components such as the magnets, controllers, and wiring were embedded directly into the structure of the motor. The end result was a custom-built, fully functional motor that did not require any post-printing assembly. Similarly, MacDonald et al. [6] compared the use of AM (via direct write conductive inks and stereolithography) to traditional injection molding for the purposes of prototyping and manufacturing an electronic gaming die. The researchers found that the time to market could be significantly improved using AM compared to traditional manufacturing. They estimated that the additive method was at least 400% faster than the traditional method. By harnessing the capability to direct write and embed electronic circuitry into the products, they could be evaluated for fit, form, and function simultaneously. Klomp [4] explored the use and applications of the material extrusion method with conductive filaments. The researchers printed a capacitive touch wheel and a capacitive touch sphere using dual extrusion and conductive filament. By connecting the capacitive sensors to Arduinos, they were able to use them to control LED lights, music, and even video games. While these are only a few examples of how multifunctional AM has been utilized in product design, they nevertheless capture the possibility offered by multifunctional embedding or direct write.

2.2 Direct Write

Direct writing describes processes that can deposit thin layers of conductive materials at very high accuracy to support the creation of multifunctional structures. Hon [7] discusses many different methods of direct writing, including inkjet, laser, and mechanical systems. Direct writing is usually but not always related to electronic circuitry and conductive materials. As an additive process, direct writing offers many similar advantages such as reducing waste material, enabling greater design flexibility, and speeding up the manufacturing process [8]. There is significant overlap between technologies used for direct writing and for additive manufacturing. For example, extrusion-type direct write machines are very similar in basic function to a common material extrusion 3D printer. Inkjet and aerosol jet direct writing is similar to the polymer jetting method of additive manufacturing. However, compared to AM (especially material extrusion), most forms of direct writing are designed for specialized purposes and not easily accessible to an average user.

There has also been significant research into the impact of design and processing on the conductivity of direct-write traces. For example, Perez [9] deposited silver conductive ink and embedded it into various geometries during the material jetting process, and the resistivity was observed. Encapsulating the conductive ink with non-conductive material was found to significantly increase the resistivity of traces compared to fully-exposed conductive ink. The researchers concluded that, due to the high resistivity of their sample traces, they would not be well suited for high power applications. However, they demonstrated that the method could be used for strain gauge and capacitive sensor applications.

2.3 Conductive filament

Currently, multifunctional printing and direct writing are out of reach of many hobby-level users, due to the need for expensive conductive inks and specialized equipment. In recent years, researchers and manufacturers have been working to develop carbon-composite filaments that would be capable of being used with common desktop-scale material extrusion printers. Since material extrusion is by far the most widely accessible form of AM, this would allow multifunctional printing to reach a much wider audience. Of course, the filament must not only be accessible but also sufficiently conductive. While matching the resistivity of direct write inks would be ideal, higher resistivity can still be useful for sensors and gauges, as stated by Perez [9].

In general, conductive filaments are created by adding carbon to standard filament in order to improve its properties. By mixing small quantities of these materials into standard filament, the filament will takes on some of the properties of the carbon material, but can still be heated and extruded normally. Ibrahim et al. [3] performed an initial study on the resistivity of Protopasta conductive PLA under different lengths and volumes, and compared its resistivity to a conductive ABS filament. The researchers tested the resistivity of different lengths of the filament (before extrusion), as well as the resistivity of single strands of extruded filament. In both cases, the resistivity was found to be abnormally high within the first 10 mm of filament, quickly dropping down to a more consistent level around 20 mm. They found the resistivity of the extruded filament to be around 0.25 ohm-meters, which correlates with ProtoPlant's claims. Klomp [4] tested several different conductive filaments, including Protopasta conductive PLA. They observed a resistivity of 0.46 ohm-m along the layers of a 3D-printed cube, and 0.84 ohm-m across the layers. Protopasta was found to be the best of the filaments they tested, being both the least resistive and the easiest to print. The numbers they observed are somewhat higher than Ibrahim and Protopasta's claims.

As this review of literature has shown, existing work has emphasized the mechanical properties and some potential applications of conductive filaments. However, the aspect of design for additive manufacturing with these new filaments has largely been ignored. This aspect is particularly important since it is unknown how the resistivity of these filaments can vary based on different conditions, including print parameters and part geometries. The goal of this research is to try to address this gap in knowledge. With a better understanding of the effects of different parameters, users will be able to design and print multifunctional parts with resistivity that better matches the designer's intended application.

3. EXPERIMENTAL APPROACH

There are three primary objectives of this research study. The first is to investigate the effects of print parameters on the resistivity of conductive filaments, including nozzle temperature, layer height, extrusion speed, and travel speed. The second objective is to investigate the effects of print geometry on resistivity. This includes part orientation as well as single strands compared to printed blocks. The third objective is to investigate the effect of enclosing conductive material using a dual extrusion process. The work presented will determine which parameters and geometries will produce the lowest resistivity in the printed traces and will act as a guide for designers looking to maximize the effectiveness of these traces in low-cost printed electronics.

3.1 Materials and equipment

The printer used in this experiment is a Lulzbot TAZ5 fitted with a dual extrusion head. It was chosen for this experiment due to its versatility and compatibility with a dual extrusion head as well as custom filament materials [10]. The printer was controlled with Cura slicing software, which contains pre-made "quickprint" parameters for hundreds of unique filaments, one of which is Protopasta conductive PLA [11].

An important difference between material extrusion and other forms of manufacturing is that parts made with material extrusion exhibit significant anisotropic properties affected by the orientation of the layers compared to the mechanical or electrical load [12]. As such, build orientation nomenclature is essential. According to ASTM standards [13], part orientation is named with the longest dimension first and the second-longest dimension second. X and Y are the two horizontal dimensions and Z is used for the vertical dimension. As shown in Figure 1, the XY orientation refers to a part lying flat on the build plate, the ZX orientation refers to a part standing vertically like a column, and the XZ orientation refers to a part lying horizontally on its edge. The authors use this standardized naming approach throughout the paper.

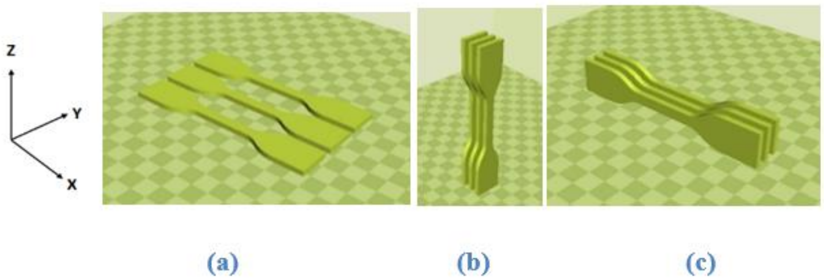

Figure 1. Specimens on the build platform in various orientations: (a) XY, (b) ZX, and (c) XZ.

The two conductive filaments described previously were tested: Protopasta conductive PLA and BlackMagic conductive graphene filament. Protoplant claims that its conductive PLA filament can achieve up to 0.3 ohm-m in-plane with the layers and 1.15 ohm-m perpendicular to the layers (in the ZX orientation) [14]. As previously discussed, Ibrahim et al. [3] were also able to observe a resistivity of approximately 0.25 ohm-m. The second conductive filament is Conductive Graphene Filament made by BlackMagic3D. The company claims that the filament has a volume resistivity as low as 0.006 ohm-m [15].

3.2 Selection of independent variables

Four independent variables were chosen to be analyzed in the initial set of experiments: Print temperature, layer height, extrusion speed, and travel speed. Once some consistent trends were established with the initial horizontal (XY) experiments, the vertical (ZX) experiments only looked at layer height as the independent variable. Finally, the independent variable for the dual extrusion experiments was how much of the conductive sample’s cross-sectional perimeter was enclosed.

Five levels were chosen for each independent variable, summarized in Table 1 below. The levels were chosen based on recommended manufacturer settings and common 3D printer settings. In addition, manufacturability was used to determine the range of parameters. For example, test samples would not print reliably below 200ºC or above 240ºC. At temperatures below 200ºC, the filament was not hot enough to extrude, while at temperatures above 240ºC, the extruded filament would flow excessively and would not adhere to the intended structure.

Table 1. Table of independent variables and parameters

Temperature (C)	Layer Height (mm)	Extrusion Speed (mm/s)	Travel Speed (mm/s)
200	0.2	10	140
210	0.3	30	160
220	0.4	50	180
230	0.5	70	200
240	0.6	90	220

3.2 Single Strand Samples

The first part of the experimentation consisted of testing single strands of filament, for both Conductive PLA and graphene materials. The samples were printed with nominal dimensions of 0.5 mm x 0.5 mm x 30 mm; however, due to the flexibility of extruded material before cooling and the use of different layer heights, the actual dimensions of the samples varied. For example, the strand printed at 0.2 mm layer height had a height of 0.2 mm and a width of 0.8 mm.

Meanwhile, a layer height of 0.5 mm would result in dimensions closer to 0.5 x 0.5 mm. Among samples with the same nominal dimensions, the physical dimensions varied by about ±0.05 mm. The cross-sectional width and height of the samples were measured using a Neiko digital caliper with an accuracy of 0.02 mm.

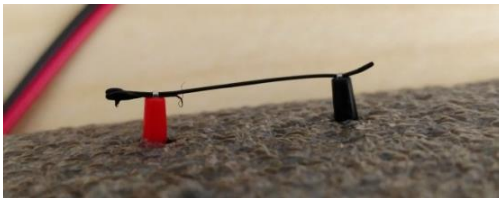

Figure 2. A single strand sample being tested for resistivity

The resistance of the samples were tested using a Hewlett-Packard 972A handheld multimeter. The accuracy for ohm measurements is 0.2%. The hook leads were pushed through a block of foam to maintain a constant 20 mm distance. The distance between the leads was confirmed via digital caliper. The resistivity was then determined by using the equation

$$Resistivity\ (ohm * m) = \frac{Resistance\ (ohm)\ *\ width\ (m)\ *\ height\ (m)}{length\ (m)}$$

The conductivity could then be found by taking the inverse of the resistivity. To analyze trends across multiple changing variables, a Response Surface Methodology (RSM) was used. Minitab was used to generate a full response surface design, consisting of 31 runs, for the horizontal single-strand testing. For each run, three samples were printed using the parameters defined in the run.

3.3 Horizontal Block Samples

The second geometry was a thin, rectangular block, designed to test the layer-on-layer and road-to-road effects of printed filament. The dimensions of the block were 1.5 mm x 1.5 mm x 30 mm. There was a difference of up to ±0.2 mm in the measured dimensions compared to the nominal dimensions. The samples were attached to the multimeter using alligator-type leads, shown in Figure 3. This method was used to measure the resistivity along the layers (in the XY orientation). The same response surface design used for the single strand testing was used again here. This included 31 different runs and 3 samples tested for each run.

Figure 3. A horizontal block sample being tested for resistivity

3.4 Vertical Block Samples

The third geometry was similar to the second, but this time printed in the vertical (ZX) orientation so that the layers were stacked on top of each other. However, printing in the ZX orientation is much more unstable since the base size is very small and tall samples tend to wobble when nearing the top of the print. Because of this, 2 x 2 mm dimensions were chosen for the vertical sample. Figure 4 shows an example of a 2 x 2 mm vertical sample. The samples were measured in the same fashion, but due to the different orientation, the resistivity across layers (ZX orientation) was now being measured.

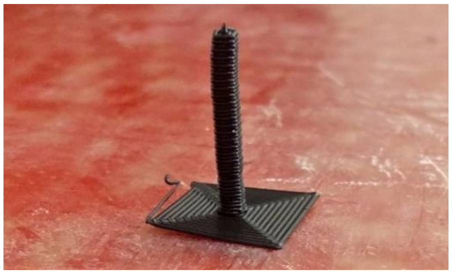

Figure 4. A 2 x 2 mm vertical sample with a layer height of 0.5 mm

After a set of optimal build parameters had been determined from the horizontal testing, they could be used to narrow down the experimental variables for this geometry experimentation. Print temperature was held constant at 240°C, extrusion speed was held at 50 mm/s, and travel speed was held at 180 mm/s for the conductive PLA material. For the graphene filament, the print temperature was held constant at 230°C, extrusion speed was held at 30 mm/s, and travel speed was held at 180 mm/s. The only independent variable for the ZX oriented specimens was the layer height, which again ranged from 0.2 mm to 0.6 mm in 0.1 mm increments.

3.4 Dual extrusion samples

Finally, dual extrusion samples were tested in the horizontal (XY) and vertical (ZX) orientations. In the horizontal sample, the central non-conductive section was exactly 20 mm long and the ends of the conductive section were left exposed. This was done so that the alligator clips could be attached right against the central section, ensuring a constant distance for measurement.

Figure 5. Horizontal and vertical dual extrusion samples.

In the vertical orientation, the sample geometry had to be changed. In order to print the previous sample in the vertical orientation, the non-conductive sheath would have to be printed in the air. The geometry was too small to attach support material below the sheath. Printing would cause the sheath section to sag during the build process, making measurement inaccurate. Instead, a new sample and method of measurement was chosen. The sample and sheath were both printed to be

20 mm tall. To measure the resistance, copper tape was attached to the top and bottom ends of the sample, which were then connected to the multimeter via alligator clips. For the dual extrusion testing, the only independent variable was whether or not the conductive sample was encased by a non-conductive sheath. The samples were printed using the same parameters discussed previously. All horizontal samples were printed at 0.2 mm layer height, and all vertical samples were printed at 0.6 mm layer height.

4. RESULTS AND ANALYSIS

As discussed in Section 3, response surface methodology (RSM) was used to analyze the results of the experiments. The RSM method fits a second-order polynomial to the model. In a RSM analysis of variance, the linear p-value determines the significance of a linear trend. The square p-value determines the significance of a parabolic trend. A parabolic trend suggests that the variable has a maxima or minima, unlike a simple linear relationship. The parabolic trend can be independent of the linear trend, so there does not need to be a significant linear p-value in order for the square p-value to be valid. In addition, the RSM analysis of variance also determines the relationship of interaction effects. A statistically significant two-way interaction effect can be confirmed as long as one of the individual main effects is also significant.

4.1 Single Strand PLA Samples

Assuming that a p-value of 0.05 or less denotes statistical significance, it can be seen in Table 2 that there is a significant linear main effect for both nozzle temperature and extrusion speed with respect to the resistivity of the sample. There is also a significant parabolic main effect for temperature. This indicates that the relationship between temperature and resistivity can be described as a parabola. By looking at the following main effects plot in Figure 6, we can see the trends suggested by the data.

Table 2. Analysis of Variance for the Single-Strand Conductive PLA samples.

Variable	p-value
Temperature	<0.001
Extrusion Speed	0.047
Temperature*Temperature	0.007

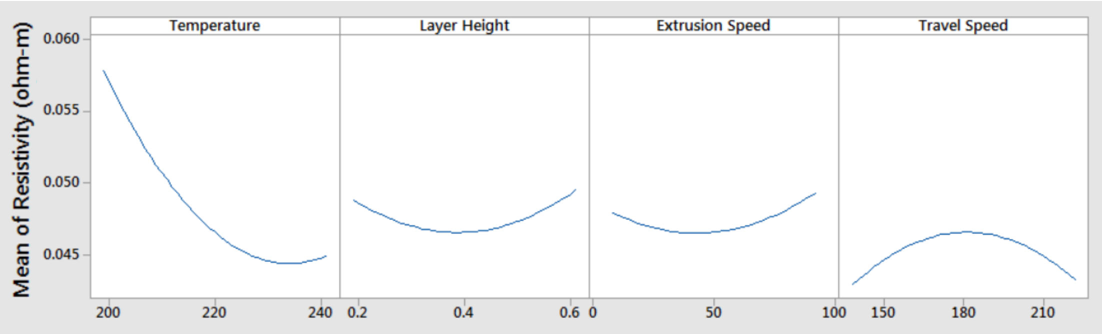

Figure 6. Main effects plot for the single-strand conductive PLA samples.

The analysis of variance says that the temperature plot on the far left of Figure 6 is statistically significant, both in the linear and parabolic relationships. The resistivity is at a minimum around

230ºC. This correlates with Protoplant's recommended print temperature. The layer height and travel speed plots are not statistically significant. For extrusion speed, the analysis of variance says that the linear trend is significant, but the parabolic trend is not. In other words, resistivity generally increases with greater extrusion speed, but there is probably not a significant local minimum as suggested by the plot.

It makes intuitive sense for higher temperature to result in lower resistivity. Zhang et al. [16] suggested that the extrusion process affects resistivity by orienting the conductive particles. A higher printing temperature increases the filament viscosity [17], which may allow the particles to flow more freely and better distribute themselves within the filament instead of getting agglomerating. An extrusion speed that is too high may lead to inaccurate deposition [17], which could cause the conductive particles to be further apart than desired. Conversely, an extrusion speed that is too low may cause clogging and inconsistent deposition. In this case, the layer height is not significant because only one layer was printed; its largest effect was changing the dimensions of the single layer. Also, travel speed is not significant since only a single strand was printed, so there are no actual travel movements.

The measured resistivity of the single-strand filament ranges from 0.045 ohm-m in the best-case scenario (print temperature at 230°C) to 0.055 ohm-m at a print temperature of 200°C. In comparison, Ibrahim [3] observed a value of 0.25 ohm-m for single-strand extruded filament, with print temperature in the range of 210ºC to 230ºC. The observed resistivity was around 80% lower than Ibrahim’s data. This may be due to the use of a different method of measurement.

4.2 Single Strand Graphene Samples

For the graphene samples, only temperature was found to have a statistically significant effect. Again, temperature had a parabolic relationship with a minimum resistivity at 230ºC. The overall resistivity was only a small amount lower than the Conductive PLA, with a range of about 0.01 ohm-m to 0.05 ohm-m.

Table 3. Analysis of Variance for the Single-Strand Graphene samples.

Variable	**p-value**
Temperature	<0.001
Temperature*Temperature	0.039

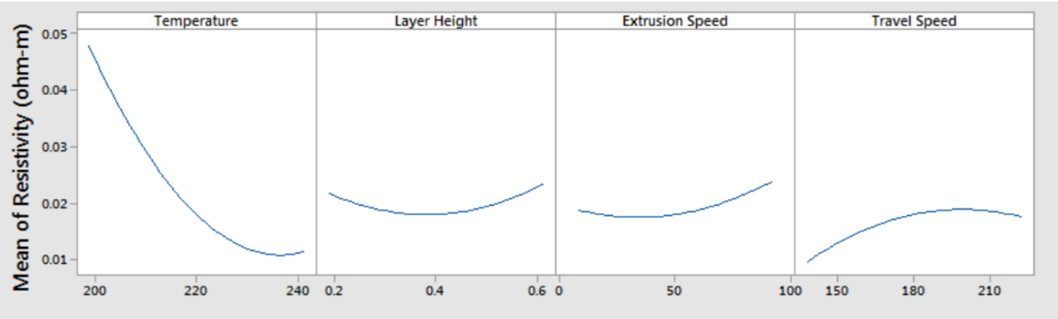

Figure 7. Main Effects Plot for Single-Strand Graphene samples

This measured resistivity is approximately 2-8 times larger than the resistivity claimed by BlackMagic for their filament. This could be due to a number of factors. First, BlackMagic did not specify whether their value was measured based on a printed sample or if it was based on a pure block of graphene. Second, when measuring very low resistances, the magnitude of any possible errors are magnified. While the actual resistances that were being measured should be well within the capability of the multimeter, any sort of error caused by an imperfect connection to the sample or an incorrect caliper measurement could have a significant impact on the result. For instance, the measurement error of the calipers is ±0.02 mm, which is up to 5% of a single dimensional measurement. When combined with the 3 dimensions, and the fact that an error in length may also affect the measured resistance, the effect of caliper error could be 15-20%.

4.3 Horizontal (XY) Block PLA Samples

The analysis of variance for the PLA horizontal block samples shows that both temperature and layer height were statistically significant based on a linear relationship. However, the parabolic relationships were not significant. This suggests that higher temperature (240ºC) and lower layer height (0.2 mm) tend to reduce resistivity in the horizontal (XY) orientation. The effect of extrusion speed was found to be not significant in the linear but significant in the parabolic. This suggests that there is an ideal extrusion speed at approximately 50 mm/s, and going too far below or above this speed will cause resistivity to increase. The effect of travel speed was again not found to be significant.

Table 4. Analysis of Variance for the Horizontal Block Conductive PLA samples.

Variable	p-value
Temperature	<0.001
Layer Height	0.002
Extrusion Speed*Extrusion Speed	0.009
Temperature*Extrusion Speed	0.029

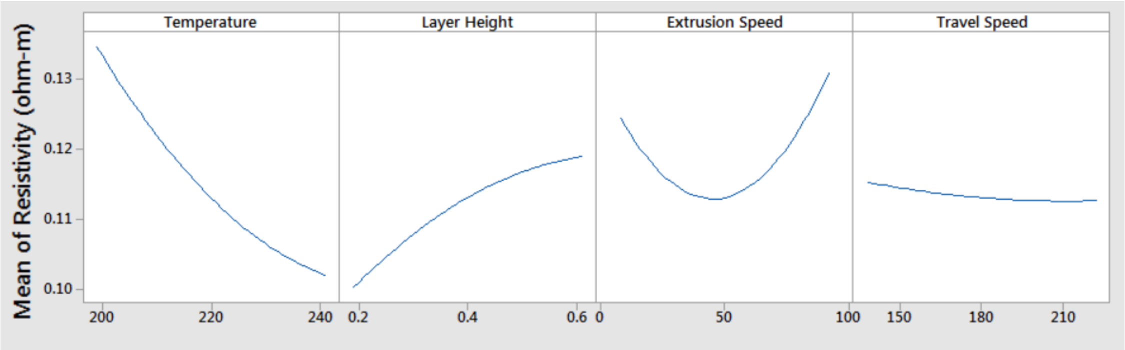

Figure 8. Main Effects Plot for the Horizontal Block Conductive PLA Samples.

The analysis of variance also shows that there is a statistically significant interaction between temperature and extrusion speed. A higher extrusion speed is more desirable as the print temperature increases. While the overall minimum resistivity seems to occur at an extrusion speed in the range of 40-50 mm/s, the minimum resistivity for a print temperature of 240°C seems to occur at an extrusion speed between 50 and 70 mm/s. The temperature and layer height results align with the original hypothesis that higher temperature and lower layer height would reduce resistivity. As stated earlier, a higher temperature may allow the conductive particles to flow more freely. The effect of lower layer height is also as expected. Lower layer height means that the dimensions of the block are filled more completely and there are fewer gaps between printed roads. This should result in less contact resistance as the current flows in the direction of the layers.

The observed resistivity for each of the block samples is much higher than the single-strand samples, which makes sense since contact resistance now plays a much greater role in overall resistivity. Based on the contour plot, it appears that an ideal sample printed at 240ºC with 0.2 mm layer height and 50 mm/s extrusion speed should have a resistivity of close to 0.1 ohm-m. In comparison, the manufacturer claims a resistivity of 0.25 ohm-m for printed parts in the XY orientation [14], and Klomp observed a resistivity of 0.46 ohm-m in the XY orientation [4]. The resistivity observed this study is about 60-80% lower. One potential explanation for this discrepancy is the difference in sample geometry. The standard sample geometry for volume resistivity testing is a 10 mm cube, and this is what was used by both the manufacturer and Klomp. However, Ibrahim [3] found that the resistivity of single-strand conductive PLA was abnormally high in the first 10 mm, dropping down to a consistent value after 20 mm. Further research should be done to see if this may have an effect on printed samples as well.

4.4 Horizontal (XY) Block Graphene Samples

For the graphene samples, only temperature and layer height were found to be significant, and this time temperature had a parabolic relationship. The temperature has a minimum at about 230ºC, which correlates well with BlackMagic's recommended print temperature of 220°C. This time the extrusion speed was found to have very little significance at all.

Table 5. Analysis of Variance for the Horizontal Block Graphene samples.

Variable	p-value
Temperature	0.018
Layer Height	0.012
Temperature*Temperature	0.040

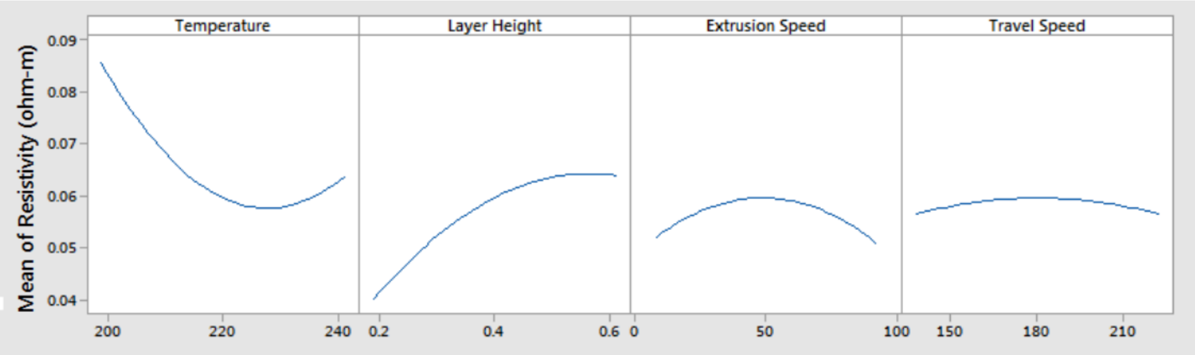

Figure 9. Main Effects Plot for Graphene Horizontal Block samples

From Figure 9, the overall resistivity ranges from just under 0.06 ohm-m to 0.085 ohm-m, which is two orders of magnitude higher than the manufacturer’s claimed resistivity. While this seems significant, as noted before, the manufacturer’s claimed resistivity may not have been measured based on a printed part. BlackMagic readily admits that "the resistivity will change depending on your print" so a higher resistivity than the ideal is to be expected [15]. In this case, it is likely that the contact resistances between the printed layers and strands are preventing the current from flowing as quickly as it could in a homogeneous block of material.

4.5 Vertical (ZX) Block PLA Samples

After several rounds of testing, the effect of print temperature was found to relatively consistent, with a temperature of 230-240ºC being the best for most samples. The effect of extrusion speed was also relatively consistent, with an optimal extrusion speed at 50 mm/s for PLA. The ideal numbers also generally match up well with the parameters recommended by the manufacturers. Travel speed has been found to be insignificant in all cases so far. Due to these findings, for the vertical (ZX) block samples, experimentation focused on the most important variable, layer height. Each layer height was tested three times, and the results were averaged. A one-way ANOVA was performed to determine the statistical significance of the effect of layer height on ZX block specimens; the calculated p-value was less than 0.001.

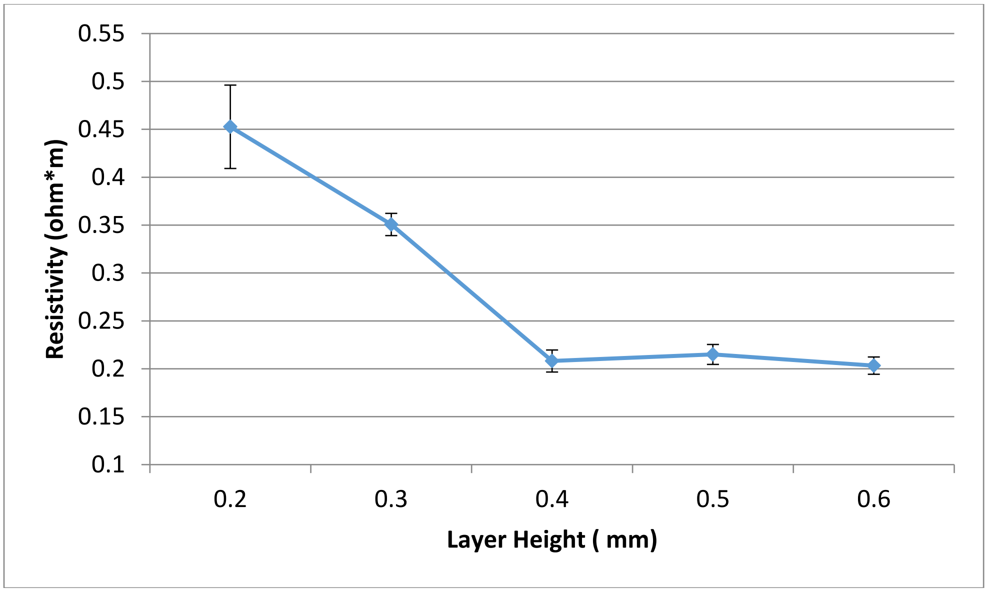

Figure 10. Plot of resistivity vs. layer height for the vertical conductive PLA samples.

The resistivity results of the vertical samples were contrary to the original hypothesis. Instead of lower layer heights causing lower resistivity, Figure 10 shows that higher layer heights result in lower resistivity. Of course, this is for the vertical orientation only - in the horizontal, lower layer heights still produce less resistivity. This result is surprising at first, but makes sense on closer examination. In the horizontal orientation, the current was flowing along the layers - as if flowing through a wire. However, in the vertical orientation, the current is flowing *across* the layers. A low layer height means a much larger number of interfaces that the current must cross, and each one has contact resistances. A higher layer height means much fewer interfaces, and therefore less resistance. See Figure 11 for a visualization. In the space of one 0.6 mm layer, there could be three 0.2 mm layers. In the 0.2 mm sample, the current would have to cross three different layers, while in the 0.6 mm sample, the current can flow unimpeded across a homogeneous single layer.

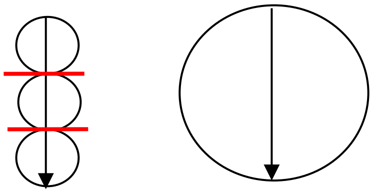

Figure 11. A schematic comparing interfaces for 0.2 mm layer height with 0.6 mm layer height.

As the data shows, the 0.4 mm layer height has almost the same resistivity as the 0.6 mm layer height in the vertical orientation. However, it has much lower resistivity in the horizontal orientation. Therefore, if a component needs to be printed using conductive filament in both horizontal and vertical orientations, then 0.4 mm layer height would be a well-balanced compromise choice. Protoplant originally claimed a resistance of 1.15 ohm-m when measuring resistivity across the layers [14], and Klomp observed a resistance of 0.84 ohm-m [4]. These results show resistivity that is around 60-80% lower. The resistivity would depend on the layer height that Protoplant and Klomp used when testing, which is unknown. If they used 0.2 mm or lower, then the results differ by the same margin as the horizontal samples.

4.6 Vertical (ZX) Block Graphene Samples

For the graphene samples, a similar decreasing trend can be seen in Figure 12, with a p-value of 0.3745. However, since the overall resistivity of the graphene samples is much lower (while the standard deviation was similar), the results cannot be considered statistically significant. Based on the behavior of the conductive PLA, it seems likely that graphene should also exhibit less resistivity with higher layer height. However, more accurate testing must be done in order to confirm this.

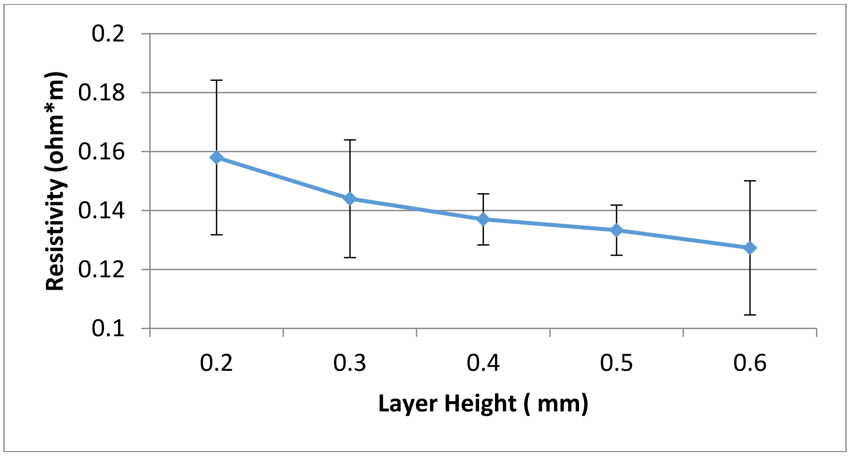

Figure 12. Plot of resistivity vs. layer height for the vertical graphene samples.

4.7 Dual Extrusion Samples

The dual extrusion experiments were conducted to see if enclosing the conductive filament with regular non-conductive filament would affect its resistivity. In an actual multifunctional part, most conductive filament would be enclosed, so this is an important factor in overall resistivity. Based on the calculated p-values for each pair of samples, the effect of dual extrusion was not found to have a statistically significant effect on resistivity in all cases.

Table 6. Dual extrusion results (XY = horizontal, ZX = vertical, SE = single extrusion, DE = dual extrusion)

	Resistivity 1	**Resistivity 2**	**Resistivity 3**	**Average (ohm-m)**	**Std Dev**	**p-value**
PLA XY SE	0.101	0.122	0.115	0.113	0.0107	
PLA XY DE	0.106	0.135	0.124	0.122	0.0146	0.647
Graphene XY SE	0.0587	0.0622	0.0683	0.0631	0.00486	
Graphene XY DE	0.0572	0.0733	0.0637	0.0647	0.00810	0.950
PLA ZX SE	0.212	0.194	0.204	0.203	0.00902	
PLA ZX DE	0.186	0.234	0.215	0.212	0.0242	0.606
Graphene ZX SE	0.134	0.146	0.102	0.127	0.0227	
Graphene ZX DE	0.167	0.128	0.175	0.157	0.0251	0.208

5. CONCLUSIONS AND FUTURE WORK

The goal of this research study was to analyze the effect of print parameters such as temperature, layer height, extrusion speed, and travel speed on the resistivity of conductive filaments. The second major goal was to analyze the effects of on resistivity. The third major goal was to determine whether dual extrusion would affect resistivity. Two different types of commercially-available conductive filament were selected, tested, and compared. Various samples were printed under a range of different parameters and geometries, and their resistivities were analyzed using response surface methodology. Based on these tests, the authors conclude that:

- Generally, higher print temperature correlates to lower resistivity, up to certain limits. Conductive PLA does best at around 240°C, and graphene does best at around 230°C. Excessively high nozzle temperatures cause unreliable extrusion.
- Smaller layer height reduces resistivity when measuring along the filament (horizontal orientation). When measuring across the filament (vertical orientation), smaller layer height increases resistivity. A good balance can be struck at 0.4 mm layer height if conductivity in both orientations is required.
- The best extrusion speed for conductive PLA is around 50 mm/s. Extrusion speed does not appear to have a significant effect on the resistivity for graphene.
- Travel speed does not appear to have a significant effect on resistivity at all.
- Enclosing a conductive trace within standard non-conductive filament does not appear to impact its resistivity.

To expand the breadth of this research, future work should focus on studying applications of this technology. The knowledge of print parameters and the effects of different geometries can be applied to the design of printed electronics, such as capacitive sensors and strain gages. Future work could study how to best use conductive material extrusion printing to produce low-cost, customizable electronic components. In addition, future work could look into the chemical composition of conductive filaments to gain a more concrete understanding of why the resistivity changes under different conditions, which may lead to more useful and versatile conductive filaments in the future. Another potential area of research would be studying a wider range of conductive filaments. In addition to conductive PLA and graphene, there are a range of other commercially available conductive filaments, including filaments that are loaded with silver or copper particles.

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