Graphite Based Semi-Conductive 3D Printing Filament

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Abstract — **In this experiment, we create and evaluate graphite-based 3D printing composite filament in hopes of determining its effectiveness as a conductive or semi-conductive 3D printing material. With 3D printable materials becoming more relevant in materials construction, the development of a 3D printable transistor would be an invaluable invention. Our results are from experiments we ran in our 3D printing lab with custom-made filaments using graphite powder in addition to the standard (non-conductive) PLA. These results show that is indeed possible to create graphite infused filament with conductive properties. Carbon is also a potential substitute for a semiconductor when in its single-layered graphene form. However, the attributes of the filament might not make a suitable replacement for conductive filament. These results show that graphite might have a place in a 3D printable transistors for the future.**

I. INTRODUCTION

With 3D printing becoming more popular, the need for a 3D printable transistor rises. Being able to have a semi-conductive filament could lead to this development. The applications for a 3D printable transistor would impact space exploration the most. If astronauts could create any parts or devices they need in space, the need to bring extra parts would disappear. In turn, rockets would weigh less because the engineers would not have to pack copious back up devices. They would merely bring the filament needed to construct all the desired materials. Companies like NASA and SpaceX have already put research into making a 3D printer that is functional in a zero-gravity environment. A 3D printer is the only equipment necessary to utilize the semi-conductive filament. Therefore, further investment into the machines necessary to utilize this filament would not be required. Thus, the 3D printable transistor would be available for use immediately, which helps cut down time to market. Before discussing how the filament is created, some terminology that will be used in the paper must be explained as prerequisite knowledge.

First, the most important is *valence band*. All atoms have what is known as a *valence band*, which is the highest energy level occupied by electrons.

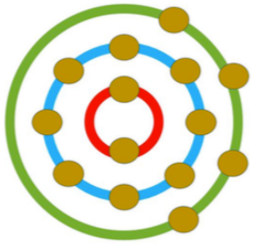

Figure 1. *This is the subatomic structure for a Silicon atom. It has the first two energy levels filled, the blue and red bands. The green band is the valence band. It needs 4 electrons to be filled.*

Silicon atoms have a unique subatomic structure that contains 14 electrons (Figure 1). Its *valence band* is indicated by green in Figure 1. Every atom wishes to either remove or fill the *valence band*. If the atom is closer to filling its *valence band* than losing it, it will try to get more electrons to fill it. Otherwise, it will give away those electrons when it bonds with another element. The number of electrons needed to fill the *valence band* is determined by which band is being filled. Silicon in specific needs eight electrons. This means silicon could either lose or gain four electrons. It is this property that makes silicon semi-conductive and a primary component in transistor fabrication. The experiments performed replaced silicon with graphite as our semi-conductive component. Graphite is primarily made of carbon, which is in same periodic column as silicon. This means it possess a similar *valence band* structure to silicon. It is for this reason that many other labs have done research into using PLA combined with graphite[2-3].

Second, *rho* and *resistivity* are both important words to know. *Resistivity* is a value that is unique to each material. It denotes the resistance of that material relative to its area and length. *Rho* is used to denote resistivity in the equation (1). A stands for area, L is short for Length, and R stands for Resistance. Length and Area are the dimensions of the material being used. Resistance determines how much electrical current will be prevented from flowing through a material when attached to an electrical source.

$$R = (\varrho * L)/A \quad (1)$$

Third, PLA is a type of plastic used in 3D printing. It is an important material used in the experiments. PLA beads were used in the research. All filaments are made using beads.

II. METHODS

Experimental Design

This experiment utilized both qualitative and quantitative data. The first few trials used graphite and PLA that was measured based on their mass. The last trials the materials were measured out based on volume instead of mass. In both the case of mass and volume, a set ratio was picked between graphite and PLA before they were mixed and placed inside the filament extruder. The temperature and motor speed for each data point was picked and then kept constant during the filament extrusion.

After the filament was extruded, qualitative analysis of the filament was taken before measuring its quantitative features. The quantitative data consisted of brittleness, mass, resistance, and conductivity.

Measurements/Calculations

The device used to make filament was a desktop filament maker as seen below. The structure of a desktop filament maker consists of a hopper for transferring materials into the device and a heating element for melting the plastic (Figure 2).

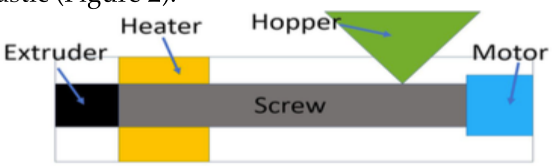

Figure 2. *Diagram of a filament extruder.*

The device used to measure brittleness was a protractor. Filament would be bent until it broke. The angle at the point of breaking determined how brittle a sample was.

The device used to measure conductivity and resistance was a generic multimeter. The multimeter was set to continuity and had alligator connectors attached to the probes. The other end of the alligator connectors was connected to the filament sample. This read the resistance with an error of 0-1 ohms, which was caused by resistance of the alligator connectors.

III. RESULTS

Silicon could not be used in filament creation because it hardens when heated. During the first trials, larger sample sizes were used and measure the materials using a mass balance. We were able to find a ratio, based in mass, that created filament that was conductive.

Each test run was made with a ratio between PLA and Graphite. For example, one test run was made with 2 parts PLA and The ratios tested were 2:1, 1:1, and 2:3. Table 1 lists the actual amounts that were used.

Table 1. *This table describes different trials. The first column describes the ratio between column two and three. The fourth column says if the filament produced was conductive.*

Ratio	PLA(g)	Graphite(g)	Conductive
2:1	35.283	17.644	No
1:1	35.045	34.519	No
2:3	28.345	42.297	Yes

Although the 2:3 ratio produced conductive filament it did not create it in a consistent manner. It also caused the extruder to clog with graphite. I observed that the reason this occurred was because larger amounts of PLA and graphite. In other words, the concentration was not kept consistent once the materials entered the chamber of the desktop filament extruder.

It was determined that the best way to handle this was to start measuring the plastic and graphite by volume instead of mass. This helps determine how much material needs to be added to the extruder to fill the chamber. Also, the size of the samples was made smaller as well. This prevents pockets of graphite and PLA from forming more frequently. The next five tests taken with these changes were better and produced consistent results. The data for these experiments can be seen below. The first two columns represent a ratio between the PLA and graphite. The cumulative volume of this ratio had to be around 2-3 tsps for the results to be consistent. Table 3 describes the ratios of PLA and Carbon used in the first two columns. The third column describes the temperature the materials were heated at while they were pushed through the filament extruder. Column four is the brittleness of the filaments produced. This quality was measured by bending the filament until it broke. The value is how many degrees the filament bent until it broke (Table 3). The sixth column is the Conductivity of the samples. These results are indicated by a N(No) or a Y(Yes). The last column is the speed at which the filament was pushed out. These values range from 0-100 and indicate the percent of power being used.

Table 2. *This table describes more trial runs. Cond. is an abbreviation for Conductivity. Temp. is an abbreviation for Temperature.*

PLA	Carbon	Temp. (C)	Brittle. (∘)	Cond.	Motor Speed
1	1	195	35	N	5
1	2	195	18	N	5
1	2	195	18	Y	10
2	5	195	12	N	5
1	3	175	2	Y	5

Qualitative observations were excluded from Table 3, so I could delve into more detail here. The first, second, and fourth samples produced a filament whose texture was consistent. They were brittle and reflected some light. All samples were a black color, which was caused by the graphite. The third and fifth trials consistently produced conductive filament, but only in bursts. Each successful result would be interrupted by a batch of hot mushy filament. Mushy in this context is supposed to refer to a filament that does not take the shape of filament. Rather it is more like a non-newtonian fluid, which in this case could also be compared to ketchup. This is why during the fifth experiment the temperature was turned down. This allowed those short bursts of non-conductive filament to retain a filament shape. The decrease in temperature had no effect on the conductive samples that were produced.

It is important to note that regardless of the ratio placed inside the mixer, any conductive filament that was made had the same appearance. All of them were extremely smooth and brittle (Figure 3).

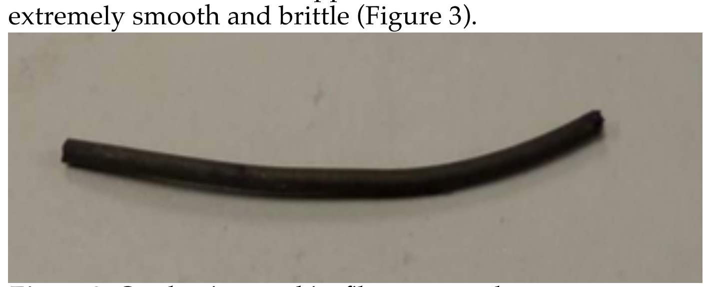

Figure 3. *Conductive graphite filament sample.*

In Table 3, the data shows that each sample had a different Resistance and Mass value. This data and two key equations can be used to prove the difference in atomic structure between samples. The following explains how reached this conclusion. Each equation has a reference number next to it for easy reference.

The first equation was mentioned back in the Introduction as equation (1).

First the density of the sample is determined (2), m represents mass, L represents the length, and A represents the cross-sectional area.

$$(2) \qquad D = \frac{m}{L \times A} => L = \frac{m}{D \times A}$$

Equation (2) is arranged so that Length is found, so this is can be combined with and substituted into equation (1) to obtain (3).

$$(3) \qquad R = \frac{\rho \times m}{D \times A^2} => A^2 = \frac{\rho \times m}{D \times R}$$

We will use a variant of (3) with a generalized subscript *i* representing each sample of Table 3, named (4).

$$(4) \qquad A^2 = \frac{\rho_i \times m_i}{D_i \times R_i}$$

Now two versions of equation (4), assuming cross sectional area is constant due to the nature of the experiment, can be created with substitutions from Table 3:

$$(5) \qquad \frac{\rho_2 \times m_2}{D_2 \times R_2} = \frac{\rho_1 \times m_1}{D_1 \times R_1}$$

Now (5) can now be manipulated to create (6).

$$(6) \qquad \frac{R_2 \times m_1}{R_1 \times m_2} = \frac{\rho_2 \times D_1}{\rho_1 \times D_2}$$

Most samples are of a similar volume and similar mass. Thus, we can assume the density of all samples are equal. Line (7) represents this assumption.

$$(7) \qquad \frac{D_1}{D_2} = 1$$

Using the above we can create the equation (8),

$$(8) \qquad \frac{R_2 \times m_1}{R_1 \times m_2} = \frac{\rho_1}{\rho_2}$$

which provides a way to study the percent difference of the resistivity of the samples rho values, against some base sample, here sample 1 of Table 3.

The percent difference was calculated relative to sample one, which is why sample 1 does not have a value associated with the fourth column of Table 3. The results are shown in Table 3, shown to the right.

Table 3. *The table shows the resistance and mass for each piece of conductive filament. The third column is the percent difference between the resistivity of the sample 1 and the sample in the corresponding row.*

Samples	Resistance	Mass	% Diff
1	59	0.104	N/A
2	80	0.146	4
3	184	0.366	11
4	443	0.327	139
5	352	0.27	129
6	123	0.373	42
7	179	0.288	9
8	165	0.776	63
9	172	0.243	25
10	97	0.288	41
11	184	0.223	45
12	85	0.298	50
13	86	0.263	42
14	63	0.237	53
15	87	0.284	46
16	137	0.218	11
17	374	0.211	212
18	76	0.234	43
19	37	0.167	61
20	64	0.202	44
21	43	0.206	63
22	84	0.173	14
23	67	0.217	46
24	107	0.197	4
25	135	0.206	16

Along with quantitative analysis, Table 3 helps confirm the earlier assumption that the density between filament samples is the same. A visual assessment of the filaments in Table 3 confirms that the length and mass have a linear relationship. This further supports the idea that the densities are the same because the linear relationship between length and mass is consistent with the density equation, (3). Furthermore, the seventh and tenth filament have the same mass, but different resistances. The group has included a picture to demonstrate the similar volumes.

Figure 4. A picture comparing the length of two conductive graphite filament samples. *Visual confirmation shows that they are similar in size. Note: The bottom piece was broken after having the mass and resistance measured. The top piece is sample 10. The bottom one is 8.*

These two samples are clearly of similar length. Despite their similar volume their resistances are dissimilar. Carbon makes up several different materials such as graphite and diamond. However, even though both of the substances are made up of carbon, they have vastly different properties. The reason the two materials have different properties is because of the carbon atom structure.

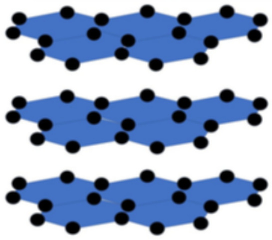

Figure 5. Atomic structure of graphite. *The atoms form layers of graphite atoms.*

Figure 5 gives a visualization of the carbon atom structure in graphite. This structure is known to be conductive. The relevance of this information is that it offers insight into the difference between conductive filament samples. Based on this evidence, it is reasonable to believe that the less conductive samples stray further away from the traditional graphite structure. The cause could be from either the inclusion of non-conductive plastic or the way graphite and PLA is mixed. The first cause needs no explanation. The second cause however could use some more detail. When the graphite is mixed in a heated chamber and pressed through a tight hole. It is possible that the atoms rearrange into a structure that while similar to the original graphite structure, are still different. Other tests and setups confirm that graphite's structure within PLA can change depending how it is pushed through [2-3]. This could lead to a different resistivity, which explains the percentage difference in certain samples.

IV. DISCUSSION

The results show that semi-conductive graphite filaments are possible. However, the filament can only be made in short bursts. Usually the extruder ends up clogging, which stops the filament from being made. The clogging is caused by the limitations of the filament extruder. The device is not powerful enough to properly mix or push the high graphite to PLA ratio without clogging. The only way for the filament to be made and not clog the extruder would be for the filament to be followed by non-conductive filament. The latter provides the pressure necessary to push the former through the extruder. In addition, it is difficult to maintain the proper concentration of PLA and graphite. Even if using small amounts of materials at a time were 100% effective at maintaining the ratio, it still would require the constant attention of the user to achieve the desired results.

V. CONCLUSION

Overall, the results of these experiments help verify the difficulties of using graphite as a silicon substitute in 3D printing. In the future, it might be prudent to find a way to more effectively mix the components before pushing them through the extruder nozzle. This would allow larger amounts of PLA and graphite to be added at once and the consistency issue with the produced filament. Various experiments have confirmed it is possible to create consistent results or improve certain qualities with different setups or procedures [1,6-7].

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Conceived and Designed Analysis, Collected Data, Contributed Data, Performed Analysis, Wrote Paper

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