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The Suitability of 3D Printed Plastic Parts for Laboratory Use

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Abstract

3D printing has become popular for a variety of users, from industrial to the home hobbyist, to scientists and engineers interested in producing their own laboratory equipment. In order to determine the suitability of 3D printed parts for our plasma physics laboratory, we measured the accuracy, strength, vacuum compatibility, and electrical properties of pieces printed in plastic. The flexibility of rapidly creating custom parts has led to the 3D printer becoming an invaluable resource in our laboratory and is equally suitable for producing equipment for advanced undergraduate laboratories.

I. INTRODUCTION

Additive printing of material, commonly known as 3D printing, has the potential to revolutionize manufacturing for both industrial and consumer use.[?] These devices come in different sizes and configurations and print with a variety of substances including plastics, metals, ceramics, and organic material. The most inexpensive versions currently print in plastic and cost less than $3,000, with entry-level ones costing less than $1,000. One of the most popular and least expensive printers, the RepRap, is an open source design that has the ability to fabricate many of its own parts.[?]

3D printing of laboratory equipment has several potential advantages including significant cost savings, customization of a standard part for a specific function, and rapid access when compared to ordering from a commercial source. Pearce[?] and his group have designed, printed, and tested a variety of different laboratory equipment and recently published a book on using RepRap printers and open source microcontrollers.[?] They have also developed a library of open-source files for printing optics equipment and found a cost savings of up to 97% compared to the equivalent objects purchased commercially.[?] Their designs are available at no cost on the web site Thingiverse,[?] a portal for open source designs of a variety of objects.

While cost-savings, rapid customization, and production are all significant advantages, it is important that printed parts be of suitable quality to not add new sources of error to an experiment beyond what might be expected from the equivalent commercially available equipment. Recently, experimenters have begun studying the properties of printed parts in order to determine their suitability for a variety of laboratory conditions. For example, Tymrak[?] measured the mechanical properties of different plastics from a RepRap printer and found that they were comparable to those produced by commercial vendors. Povilus[?] measured the compatibility of a variety of materials (glass, acrylic, plastic, and sterling silver) for ultrahigh vacuum environments ($< 10^{-8}$ torr). These were produced by higher-end EOS printers[?] and, unsurprisingly, only sterling silver had a low enough outgassing rate to be suitable for experimental use under these conditions.

In this work, our primary goal was to determine the suitability of printed objects for a plasma physics laboratory where the required pressures are more moderate. However, our experimental parameters are typical for many applications and these results should be relevant to experimenters in a large variety of fields and to teachers designing equipment for advanced educational laboratories. Our experimental conditions include pressures as low as 10^{-6} torr, voltages on metal electrodes ranging from 0.5 - 15 kV at frequencies that range from DC to 200 kHz.

After a brief description of the printer used for these measurements (Sec. II), we present our results on the accuracy (Sec. IIIA) of a printed part by comparing the dimensions of the part to the dimensions of the drawing used to create it. Strength (Sec. IIIB) of these plastic parts was determined by measuring the maximum load before breaking. Vacuum compatibility (Sec. IIIC) was determined by looking at the outgassing of the plastic at various temperatures. The electrical (Sec. IIID) properties of printed parts was estimated by printing plastic insulators around high voltage electrodes and observing the plasma discharges produced. Finally, we give some general examples of how we are using 3D printed parts in our laboratory.

II. 3D PRINTER

While there are a variety of printers currently available for purchase and one can build the RepRap, we chose to use the Replicator 2 from Makerbot Industries[?] based upon the cost, maximum size of objects that can be printed, resolution, and reliability. The printer offers a maximum build volume of 28.5 cm x 15.3 cm x 15.5 cm and a minimum layer height of 100 μm. The manufacturer claims a positioning precision of 11 μm in XY and 2.5 μm in Z, though we found (see below) that the error in accuracy was significantly larger than the precision. The Replicator 2 prints only in polylactic acid (PLA), a biodegradable plastic commonly made from corn starch or sugar cane. PLA for this printer is sold in 1 kg spools of 1.75 mm diameter filament that is heated by the printer to a temperature of 230°C and extruded through a 0.4 mm diameter nozzle. Individual layers of plastic are extruded in the X-Y plane and then the distance between the extruder and the build platform is increased in the Z-direction and another layer is printed. This continues until the full three dimensional object is completed.

To do this, software provided free by the manufacturer converts a *STL, *OBJ, or *THING file produced by most computer aided design (CAD) software into horizontal slices (the g-code) that provides instructions to the printer of where to extrude plastic in X,Y, and Z. There are several excellent free examples of CAD software such as openSCAD,[?] SketchUp,[?] 123d Design,[?] or Blender[?] that can be used if a commercially available option is not available.

In general, one prints a complete object from start to finish, but it is also possible to modify an object during or after a print. For example, one can directly print a hole that includes threads sized to match a screw (and of course one can print a screw), but it is simpler to simply print a properly sized hole and cut the threads with a normal tap used to create threads in metal. One can also embed other material into the plastic if necessary. (see Sec. IIID) In one of our experiments, we made a sandwich of PLA insulation around a thin sheet of copper that served as one electrode of our system. To manufacture this, we paused the printer when it was 50% complete, placed the copper onto the exposed top layer of the print, and then resumed the print. That way, we were able to have insulation of equal thickness on both sides of the copper.

III. RESULTS

A. Accuracy

The software provided with the printer has three default resolutions settings of low, medium, and high which correspond to a layer thickness of 300 μm, 200 μm, and 100 μm respectively. The user controls the layer thickness, the number of outer layers that are printed (the shells), and the percentage of the object that is solid (the infill) from 10 - 100%. (See Fig. 1) Two solid shell layers are sufficient to create a rigid body even for an infill of 10%.

In general, print speed is proportional to layer thickness, e.g., an object printed with 200 μm layers takes half the time of the same object printed at 100 μm layers. At a 300 μm layer height, print speed is relatively fast and is helpful for quickly testing the printability of a newly designed object. However, the thickness of the individual layers gives a surface roughness that we deemed insufficient for our needs and we did not use this setting in any of our tests.

We tested a variety of shapes (pyramid, cone, cube, cylinder) and compared the measured dimensions with the original CAD drawing dimensions. Each object was printed at least twice and the measurement of the dimensions taken three times and averaged. Errors were consistent, regardless of the shape of the object though, interestingly, one dimension in the x-y plane was smaller than the requested dimension while the other two dimensions were larger. Overall, cubes of varying dimensions had errors on the order of 50 μm for a layer thickness of 200 μm. Clearly, for high precision objects 3D printing is not suitable, but there are many applications in the laboratory where this level of dimensional accuracy is more than sufficient.

B. Strength

Given that these are plastic parts, an obvious question is how strong they are and what load is required before they will deform or break. Tymrak recently measured tensile strengths and elastic moduli for both ABS and PLA plastic for a variety of open source printers.[?] For PLA, they found an average tensile strength of 56.6 MPa for solid samples and noted that different printers have variations in nozzle size, print speed, extruder temperature, infill geometry, and other factors that can influence the measured strengths. They also noted that printed PLA is comparable in strength to conventional injection molding.

For comparison, we printed test bars that were 0.125 x 0.5 x 6 inches with varying infill percentage. The bars were pulled lengthwise by the ends up to a maximum load of 1,000 lbs on a Tines Olsen Model 1000 Universal Testing machine until the sample broke. All test pieces were printed so that the externally applied load was distributed along the layers rather than across them. In other words, we wanted to make sure that we were not measuring the force needed to separate individual layers, which is much smaller than the force needed to break an object when applied along the layers. (See Fig. 2)

For an experimenter concerned about the load on a printed object, this is an important design concern. Fortunately, it is a simple issue to address and, in most cases, one can simply orient the virtual object before printing so that the layer axis is always perpendicular to the expected direction of the experimental load.

Printed test pieces were varied by infill percentage, from 100% (solid) down to 10% at a room temperature of 20°C. As the load was increased, there was no deformation of the samples before the fracture occurred. This is called a brittle failure, as is commonly seen in glass or ceramic rather than most polymers. The solid (100%) samples broke with an average tensile strength of 60.6 MPa, slightly higher than what was found by Tymrak on different printers. As shown in Fig. 3, as we decreased the percentage of infill, there was a linear decrease in the tensile strength with a minimum measured strength of 34.7 MPa for a 10% infill.

C. Vacuum Compatibility

Our interest in 3D printed parts for the laboratory started with the question of whether they would be suitable for the inside of a vacuum vessel at moderately low pressures (1 x 10^{-6} torr < p < 760 torr) near high voltage electrodes used to create a plasma. Typically, plastic is assumed to be a poor choice for most vacuum experiments due to the relatively high vapor pressure that introduces impurities into a clean system and causes an unacceptable increase in the base pressure of the vessel.

Our experimental setup consisted of a Residual Gas Analyzer (RGA) attached to a vacuum sealed oven capable of reaching a maximum temperature of 800°C. The oven was pumped by a 150 l/s turbo molecular pump to a base pressure of approximately 1.0 x 10^{-6} torr. Background scans from the RGA showed measurable levels of hydrogen, nitrogen, and water vapor. The vacuum chamber pressure was then vented with nitrogen gas and printed pieces of different shapes and infill percentages with a maximum weight of up to 20 g were inserted into the vacuum chamber and the background gas was evacuated. At room temperature, the RGA showed no measurable increase in the background signals and the overall base pressure did not increase, indicating that any outgassing from the plastic was insignificant at these moderate pressures regardless of the infill percentage. Our assumption is that the printed parts are porous enough that any trapped air volume is rapidly evacuated from the interior. In addition, we measured the RGA signal from the equivalent mass of PLA filament that was not extruded through the printer and again found no increase in the background signals at room temperature.

The temperature of the chamber was then systematically increased while the RGA signals were monitored. Background impurity levels increased as the temperature increased, but it was not until the temperature reached 75°C that any measurable signal due to hydrocarbons from the plastic was observed, indicated by an increase in the RGA signal for AMU values of 39 and greater. Note that this temperature threshold is much lower than the extrusion temperature of 230°C. Thus, as long as the bulk temperature of a printed part is below 75°C, it is possible to use PLA printed parts without contaminating the system at these moderately low pressures.

To confirm this result in actual experimental conditions, we inserted a test piece into the vacuum chamber of a DC glow discharge plasma experiment. After evacuating the chamber, argon gas was introduced into the system until the equilibrium pressure was to 0.1 torr. Two stainless steel electrodes were attached to a power supply and the voltage increased until the argon gas became conductive and a plasma was formed at 500 V with a current of 10 mA. The plasma was sustained for 5 hours, during which there was no measurable change in the experimental conditions (base pressure, voltage, or discharge current) and no visible change in the plastic.

D. Use as a Dielectric

A dielectric barrier discharge (DBD) consists of two electrodes separated by a dielectric barrier. DBDs have a variety of applications including ozone generation, surface modifications, water treatment, and plasma medicine. Here, we looked at how the thickness and density of 3D printed electrodes affects the formation of microdischarges from a DBD. One electrode was a thin piece of copper tape surrounded by PLA plastic and the other a cylindrical aluminum HV electrode surrounded by a layer of 6 mm thick alumina and connected to a 15 kV, 75-300 kHz, AC power supply (Fig. 4).

The printed electrodes were 12 cm long, 2 cm wide, and 0.4 cm thick, electrically grounded and located 5 mm beneath the alumina, forming a discharge gap. The DBD was operated with an Ar/Air gas mixture at atmospheric pressure and an intensified CCD camera was used to image the microdischarges at various stages of their development. Each image was analyzed by counting the number of visible microdischarges that appeared and this number was averaged over all of the images. This process was repeated for different electrodes where the only difference was the infill percentage of the plastic surrounding the copper tape was varied between 10-100%.

A typical DBD consists of a large number of low current discharges and this was observed for electrodes with 100% infill. As the infill percentage decreased, the number of discharges decreased while the current in the discharge increased and often created an electrical arc that damaged the electrode. Thus, the electrodes printed with the greatest infill percentage performed best and the ability to print dielectric material in any size, shape, or configuration provided an unmatched flexibility to quickly and efficiently test new configuration ideas for different experimental conditions.

IV. EXAMPLES

Besides their use as electrodes, we use printed parts to create duplicates of damaged or lost pieces and we design original objects for specific applications. Our most common application is to hold or clamp another piece of equipment. For example, Fig. 5a shows printed parts used to hold electrodes in our Planeterrella,[?] an aurora borealis demonstration. Fig. 5b shows a replacement handle for a piece of test equipment, while Fig. 5c shows a cooling fan for electronics (with a laboratory logo added as a whimsical touch). The versatility of the printer is such that our first reaction to an equipment need is no longer whether we can find or purchase the required piece, but can we print it.

V. CONCLUSION

In order to test the suitability of 3D printed parts for laboratory use, we performed a series of tests on PLA plastic printed by a widely available commercial printer. Strength, accuracy, vacuum compatibility, and electrical properties were all found to be sufficient for many common laboratory needs. This should be true for both research and advanced educational laboratories. The printer is now a crucial piece of our laboratory and used regularly. Additionally, a 3D printer is an exceptional tool for motivating students to learn CAD drawing techniques and they are able to readily learn how to design and build a variety of custom made parts.

ACKNOWLEDGMENTS

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[11] http://www.openscad.org

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[13] http://www.123dapp.com/design/

[14] http://www.blender.org

[15] http://planeterrella.obs.ujf-grenoble.fr

FIGURES

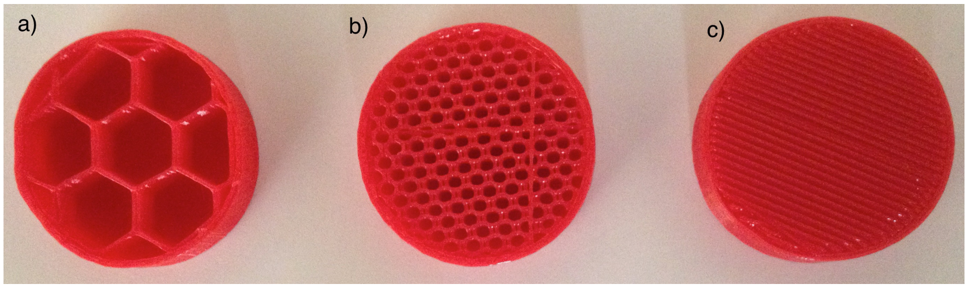

FIG. 1. A cylinder printed with 0.2 μm layer thickness, two solid outer shells, and a) 10% infill, b) 50% infill, and c) 100% infill.

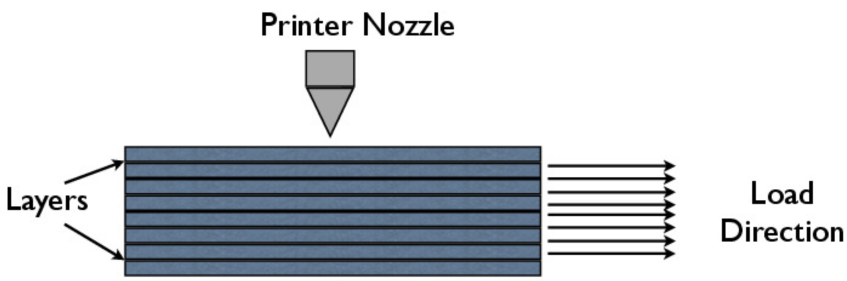

FIG. 2. Schematic of a printed bar showing the layer direction and the load direction. The printer nozzle is drawn for reference.

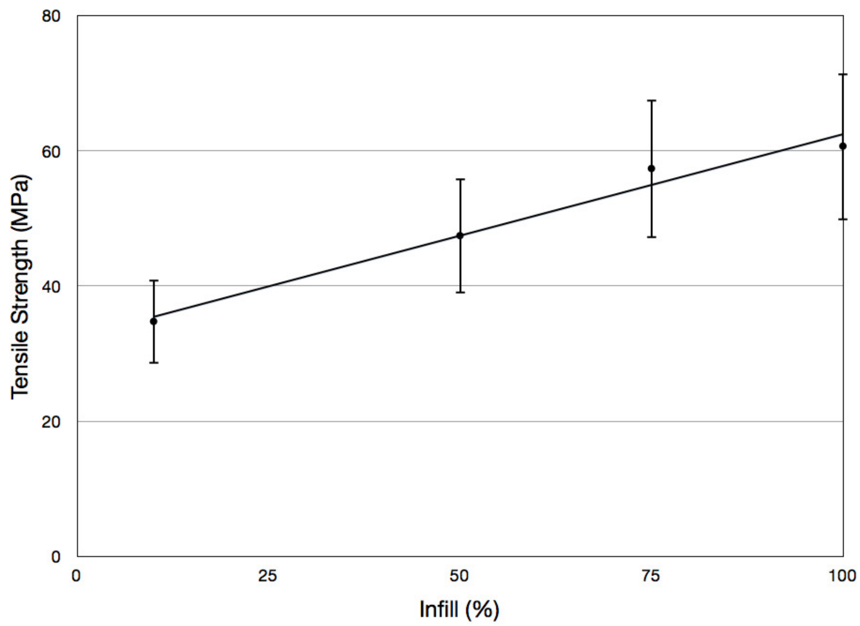

FIG. 3. Ultimate tensile strength vs. % infill

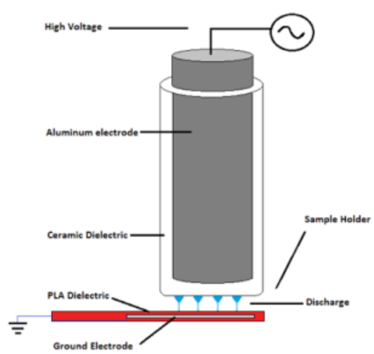

FIG. 4. Schematic diagram of a dielectric barrier discharge (DBD) showing a printed electrode used as ground.

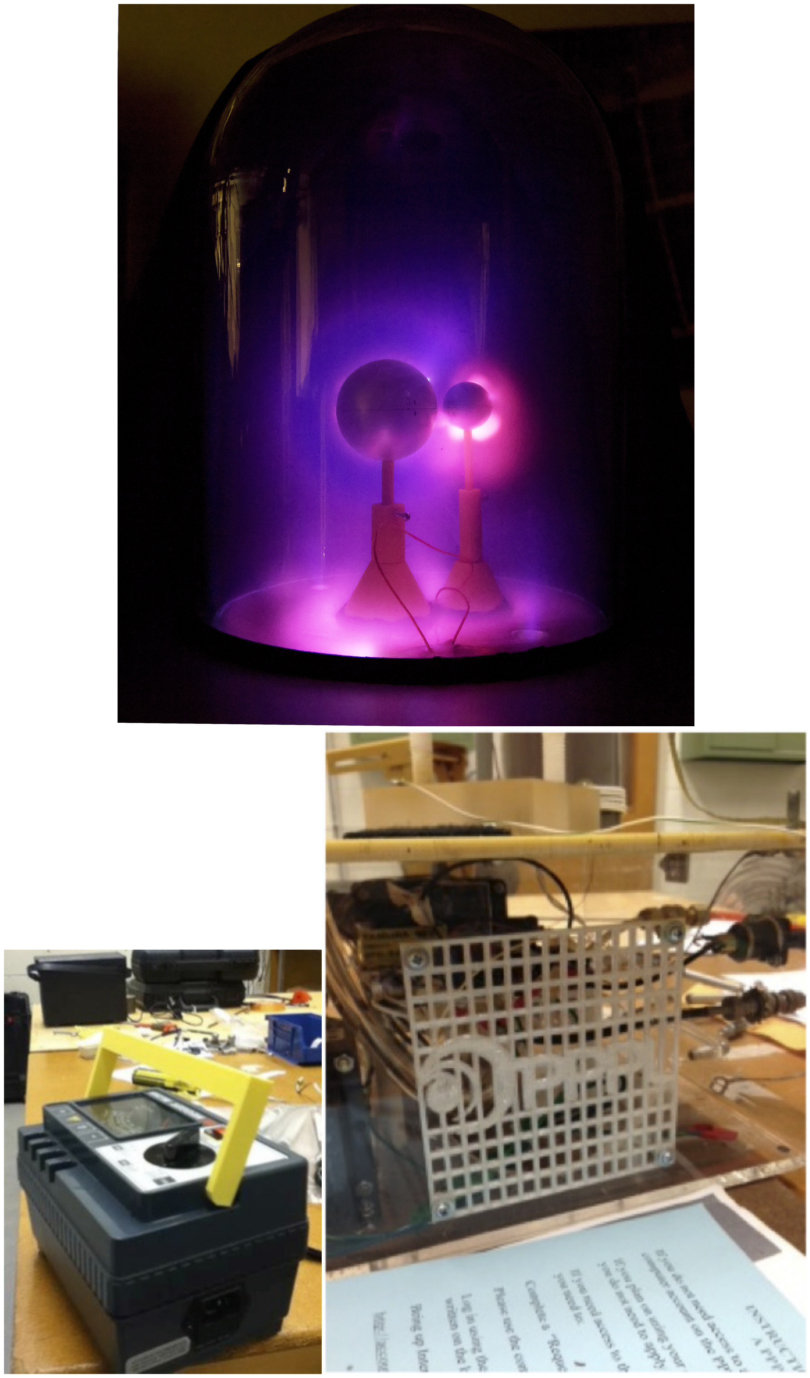

FIG. 5. Photographs of printed parts in a) Planeterrella holding up aluminum spheres, b) replacement handle, and c) protective cover.

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