The Development of a Sustainable Technology for 3D Printing Using Recycled Materials

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Abstract

As part of an undergraduate research project, a study was undertaken to determine the feasibility of extruding recyclable plastic into usable filament to create a sustainable technology for 3-D printing. An extrusion process was developed using Polyethylene Terephthalate Glycol (PETG) pellets to establish a baseline that would be used when investigating recyclable plastics. Modifications were done to allow for higher temperature extrusion to accommodate the higher melting temperature of Polyethylene Terephthalate (PET) plastics. Drying the plastic prior to extrusion was proven to be a necessary step in the extrusion process. The viscosity of the PET plastic was determined to be an important characteristic that affects the possibility of creating filament. From this study, a conclusion can be made that there are multiple key factors that will determine the feasibility of extruding recyclable plastics into filament.

Keywords: Undergraduate Research, 3D Printing, Sustainability, Recycling, Extrusion

Introduction

The consumption of 3D printing material is expected to reach 250 million pounds by 2020, and to date most 3D printer filament is made from virgin plastic [1]. In addition to the virgin plastic source material in 3D printing, there are also 33.6 million tons of plastic disposed of in the US each year, only 6.5% of which is recycled [2]. Recycled plastic bottles cannot be reformed into new bottles because this requires virgin material, limiting the sustainability of plastic bottles. Americans buy an estimated 42.6 billion single-serving (1 liter or less) plastic water bottles each year. Almost eight out of ten ends up in a landfill or incinerator and hundreds of millions end up as litter on roads and beaches or in streams and other waterways [3].

3D printing is a term to describe technology used for the rapid production of 3D objects directly from digital computer aided design (CAD) files [4]. 3D printer technology varies widely, from half-million dollar direct metal laser sintering to several hundred dollar fused deposition manufacturing (FDM) machines. Today, 3D printers can process a wide variety of materials and produce fully functional components. 3D printing technologies have been explored for a wide range of applications including robotics, automobile components, firearms, medicine, space, etc. [5]. With the advancement of both materials and 3D printing hardware, extremely precise components can be fabricated at higher speeds and lower costs [6]. It is expected that 3D printing could transform the economy, with an impact of up to $550 billion a year by 2025 [7]. The 3D printers found on most college campuses, as well as those seeing the highest consumer demand, are FDM printers, which utilize a spool of plastic filament as the source material for the 3D printing process. This consumable plastic filament must be replaced, much like the ink in a standard ink-jet printer, at a cost approaching $50 per spool. Currently printer filament is typically produced using a traditional extrusion process. While commercial printing filaments are usually polymers, such as polylactic acid (PLA) or acrylonitrile butadiene styrene (ABS), a number of composites have been used to create objects from conducting, dielectric and magnetic

materials [8,9,10,13]. There are a lot of advantages that 3D printing with plastics. These advantages are particularly valuable for research apparatus and specialist equipment for which new designs must be tested, for example, in biomedical applications, such as 3D-printed aortic valves [6,13]. 3D printing allows for more complex designs to be created than when compared to more conventional manufacturing. Plastics are inexpensive, require little energy to manufacture, and are biocompatible and lightweight. This makes them an ideal material for single-use disposable devices, which currently comprise 85% of medical equipment [11,12].
Most water bottles and other containers that are labeled with the number 1 recyclable symbol are made from the plastic PET. PET is created by the polymerization of ethylene glycol and terephthalic acid and it is used to manufacture a variety of products [14]. PET's transparency, high impact resilience, ability to create a barrier from gas and moisture, shatter resistance, and resilience to solvents are the characteristics that make PET desirable for manufacturing [15]. Although PET is a desirable material when it comes to manufacturing containers, PET is not a popular source material for 3D printing. When it comes to 3D printing, a modified version of PET is commonly used. Glycol is added to the material composition during the polymerization process of PET to create PETG. This allows for the manufacturing of a higher quality of filament when compared to PET. Although the acronyms look similar, the addition of the added glycol essentially creates a whole new plastic. The resulting filament is more transparent, less brittle and easier to use than the base form of PET [16].

The intent of this work is to evaluate the viability of using PET plastic as the source material for 3D printer filament. The process of extruding waste plastic has the potential to create an alternative use for recyclable PET bottles as a more sustainable source material for 3D printing. In addition, it will create an opportunity for future research into other recyclable plastics as a source material for 3D printers. Therefore, this work has the potential to develop a more sustainable, cost-effective, socially conscious method to meet the demand for plastic in 3D printing. This research will leverage prior efforts and utilize a custom extruder to produce 3D printer filament from both plastic pellets (PETG) as well as plastic water bottles (PET).

Methods

Construction of Custom Extruder

An extruder kit was built and used for the testing in this study. Some components of the extruder were customized to accommodate the requirements of the research. Some of the custom components include a 3D printed hopper with a lid to help reduce the amount of moisture absorbed by any plastic left in the extruder. The die used for the extrusion process was bored out to a larger size to create filament with a diameter closer to 1.75mm. A larger power supply was installed on the extruder to reach the higher temperature required to extrude PET plastics.

PETG Pellet Extrusion as Process Validation

In order to validate equipment functionality and establish a baseline, an initial extrusion process was carried out using only PETG pellets. A temperature range between 190^{o}C and 195^{o}C was used to successfully extrude virgin PETG pellets into filament. The extruder nozzle had a die that was approximately 1.80mm in diameter. The criterion that was used to establish whether or not the extrusion of PETG filament was successful was a resultant filament diameter within the range of 1.40mm to 1.80mm. This diameter range is required for the 3D printer that was used for the testing. A tighter tolerance on the diameter of the filament, with a mean of 1.75mm would be ideal given that this is one of the common standard dimensions used by 3D printers, but it was not essential for this project. Successfully 3D printing with the extruded PETG filament was enough to validate the capability of the extrusion process.

PET Extrusion

Once the process was validated, the next stage of the project was to extrude the PET water bottles. The recyclable PET bottles were shredded using a process involving a custom bottle peeler and shears made for cutting plastic. The bottles were peeled into a ribbon before being cut into small, pellet-sized pieces. The pieces were no larger than 5mm as that is the maximum size that could successfully be processed through the extruder. PET alone is very difficult to extrude because of variable material properties, so in order to achieve viable filament, glycol was added to the PET bottles. It was determined that PETG pellets added to the PET plastic was a method to add glycol and improve the material properties. The shredded PET was mixed with virgin PETG pellets in an approximately 50-50 weight-percent ratio. Prior to extrusion the blend of PET and PETG plastics was heated in an oven to help remove any excess moisture that may have been absorbed by the plastics. The oven was set to 100^{o}C and the drying time was approximately 2 hours. The plastic was weighed before and after the drying process to quantify how much moisture was lost. The plastic mixture was extruded the same day as the drying process to ensure that moisture was not reabsorbed before the plastic could be extruded. Due to a difference in melting temperature, the PET and PETG plastic were extruded at an increased temperature of 245^{o}C.

Results

Extrusion of PETG pellets using the 190^{o}C-195^{o}C extrusion temperature and 1.80mm diameter die resulted in filament with an average diameter of 1.55mm. The extruded filament was used in a 3D printer to print a square test sample (Figure 1). The square test sample was successfully printed with minimal issues. The first and last layer of the test print had slight defects caused by a thin section in the filament. Overall the print was a success and validated the extrusion process.

After successfully extruding PETG pellets, an attempt was made to extrude the mixture of PETG pellets and PET at 195^{o}C. In this attempt, the PET did not completely melt and resulted in solid pieces that were unable to pass through the die. The extrusion temperature was increased to 230^{o}C but still did not completely melt the PET plastic (Figure 2). To increase the extrusion temperature even higher, a modification was made to the extruder to increase the power supplied. Increasing the power supply also simultaneously increased the extrusion speed. An extrusion temperature of approximately 245^{o}C was necessary in order to completely melt the PET plastic. Upon raising the temperature, the mixture of PETG pellets and PET plastic was successfully extruded.

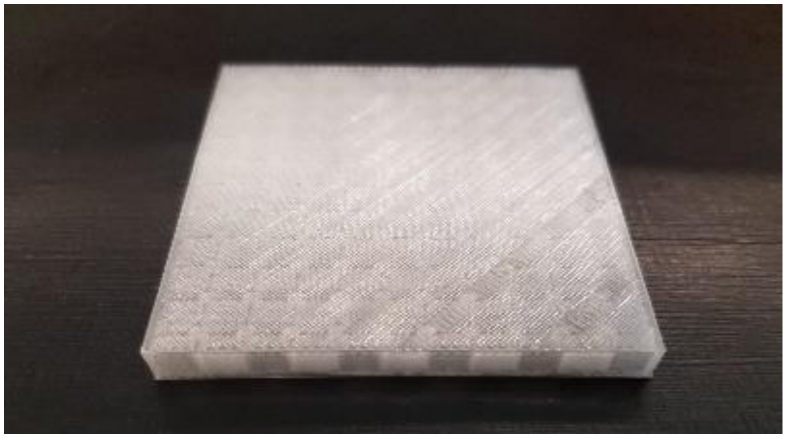

Figure 1 Test print using the extruded PETG filament. The lower right corner has some surface defects caused from a thin spot in the filament.

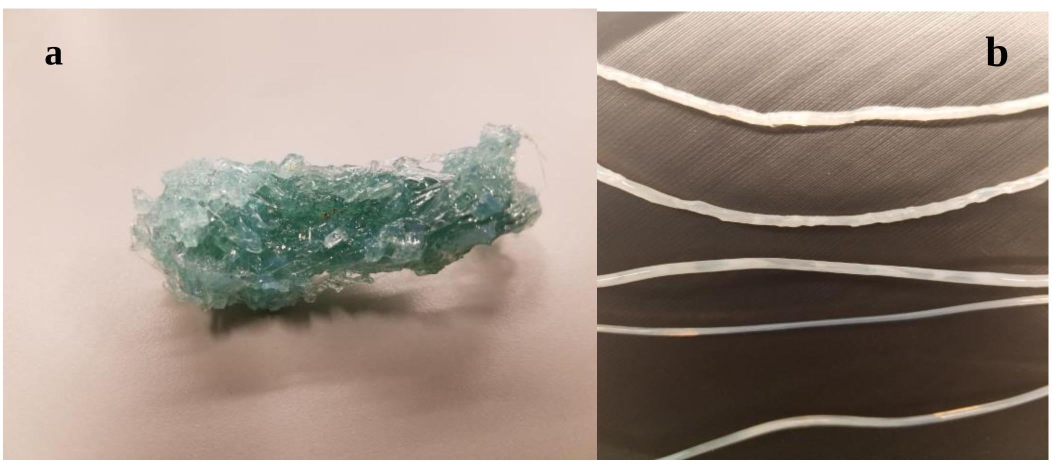

Figure 2a: Shows the PET and PETG mixture that was not able to pass through the die. The blue color is from a pigment that was added. The dark blue is the PETG and lighter color is the PET bottle plastic.
Figure 2b: Shows the improvement of the filament from modifying the extrusion process. Top shows what the filament looks like with no prior drying of the plastic. Second is what the filament looks like with 2hrs of drying but at an extrusion temperature of 230C. Last three are with 2hrs of drying time prior to extrusion and an extrusion temperature of 245C.

Originally, the filament contained bubbles that could be seen inside the filament, as well as surface deformity caused by bubbles. The presence of bubbles inside the filament was due to excess moisture that was absorbed by the plastic prior to the extrusion process. Absorption of moisture is a known characteristic of PET plastics. To correct this issue a drying procedure was done prior to the extrusion process. Baking the PET and PETG pellets at a temperature of 100^{o}C for approximately 2 hours was effective in eliminating the bubbles previously seen in the filament. A weight reduction of 25 percent was measured after drying the plastic, with initial weight at 0.4 oz and final weight of 0.3 oz. The drying procedure eliminated the bubbles caused by absorbed moisture, however, indications of inconsistent mixing of the plastic remained. The extruded filament had alternating sections of transparent and opaque coloring. The varying transparency of the filament indicated a lack of mixing of the plastics before passing through the die. In addition, there were also sections of only PET plastic that were extruded.

It was also found that when extruding the PET plastic alone, the viscosity was difficult to control. PET has a much lower intrinsic viscosity than PETG which makes it difficult to obtain the desired cylindrical shape and consistency required to create filament. This can be seen in Figure 3, which shows the difference in viscosity of the mixture vs. PET alone.

Figure 3: Left: Shows the extrusion of a 50-50 blend of PET and PETG mixture. Right: The extrusion of just the PET bottles. Notice the low viscosity and inability to create the desired filament.

Conclusions & Recommendations

A custom extruder has been constructed and has successfully extruded PETG pellets into 3D printer filament. PET water bottles have been shredded, mixed with PETG pellets and extruded, with results indicating that further research is necessary to obtain a repeatable, viable process. Based on the testing that has been done, it appears that mixing the plastics prior to extrusion is an important process to ensure that the PET plastic properties are being modified by the addition of glycol from the PETG pellets. Mixing and melting the plastics prior to the extrusion process will correct the issue of separation of the two plastics in the filament, as well as improve the issue of low intrinsic viscosity. Once the melted mixture solidifies, it can be shredded into a form capable of being passed through the extruder. The issue of low intrinsic viscosity may also be caused by the increase in extrusion speed, resulting in an increase in the amount of shear stress on the plastic during the extrusion process. To correct the increased shear a control will be installed on the extruder to reduce the extrusion speed. The results of this research indicate that with the aforementioned modifications, 3D printer filament can be successfully extruded from recyclable plastics to develop a more sustainable, cost-effective, socially conscious method to meet the demand for plastic in 3D printing.

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Jason Lehrer is a senior Mechanical Engineering major at Penn State Berks. He spent two summers doing undergraduate research as part of Penn State's Multi-Campus Research Experience for Undergraduates and was the recipient of an Erickson Discovery Grant. He is also the recipient of an Invent Penn State Grant to pursue technology transfer of the 3D printing project.

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