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CLOSED LOOP RECYCLING OF PETG IN FUSED GRANULE FABRICATION LARGE AREA ADDITIVE MANUFACTURING

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Abstract

Plastic waste is a critical worldwide problem that impacts additive manufacturing (AM). Extensive research has explored how plastic waste in AM can be reduced by recycling prints into new filament, with varying success. An alternative to filament-based extrusion is “fused granule fabrication” (FGF), which extrudes from pellets or granules. This method is often used for large area additive manufacturing (LAAM) of polymers. This paper expands upon the knowledge base from previous research on LAAM and examines the extent to which PETG can be recycled and reprinted through the same FGF tool without significant loss to its material properties. The metric used for comparing material properties is tensile testing along the direction of deposition. Recycled material was granulized, filtered, and dehydrated. This resulted in effective printing of 100% recycled PETG, with recycled samples demonstrating 83% of the tensile strength of virgin PETG.

Introduction

Large area additive manufacturing (LAAM) is growing as a method for printing large structures [14]. The most common method of LAAM for polymers is fused granule fabrication (FGF) (also known as fused pellet fabrication or FPF). Although it does not have the precision or surface quality of traditional fused filament fabrication (FFF) processes, the speed at which the material is extruded is significantly higher [17]. FGF uses a feedstock of plastic particulates, usually pellets. The feedstock is fed through a screw-driven heating chamber and extruded through a nozzle. Aside from the appeal of printing quickly there is an added benefit to this process: machining [16]. Some FGF systems can be built to include a CNC milling tool, and some, like the AMBIT XTRUDE, can even be mounted in existing CNC machines [15]. The combined capability allows for hybrid manufacturing, attaining a greater surface finish than that which was originally printed [13]. Uses for this machine and its potential includes mold making, ability to use multiple materials, composite parts, and use in the automotive industry [1].

These aspects of LAAM are appealing for higher volume manufacturing. Thanks to its rapid print speed as well as the inexpensive raw pelletized material, in comparison to rolls of filament, LAAM is becoming a desirable method for larger industries looking to make plastic parts swiftly [1]. Most polymer parts made commercially use virgin material because the cost for new materials is generally less expensive than reprocessing recycled material [18]. There has been a push for companies to “go green” and use a higher quantity of recycled materials in their plastic parts to help reduce both the quantity of plastic waste and the impact on our environment. Some estimates indicate that unless there is a change in how plastics are managed, the current trend of plastic waste will result in the weight of plastic in the oceans exceeding that of the fish that live in it by 2050 [9]. Utilizing additive manufacturing technology in industries can help reduce waste and offer sustainable value propositions for customers, but its effect is much more significant if fully recycled plastic can be used [11].

This paper explores two important aspects regarding FGF and recycling. First, the study considers the methodology needed to create granules from parts previously printed using the FGF process. Second, the study describes the process of printing with 100% recycled PETG using fused FGF methods and the resulting material properties. Previous research in FFF processes have been divided as to whether there is a significant difference in the tensile strength of fully recycled PETG in comparison to its virgin plastic counterpart. Some studies indicate that there is no difference [2], while others claim that there are significant differences, with further changes with subsequent cycles of recycling [7]. This paper examines whether there is a significant difference between virgin and full-recycled PETG for FGF processes by comparing material properties of the recycled plastic parts to virgin plastic parts in the same print orientation.

Methods & Tools

Pelletizing: The first steps taken were in determining a method to create particles small enough for the FGF tool head to use. Stock pellets are most often either cylindrical, or globular. There are other forms possible, but they are much less common [10]. We wanted to create a system that would be accessible to people with minimum equipment available, so we tried several common repurposed consumer tools in addition to an industrial granulator.

We first attempted to use a countertop kitchen blender but found that the power of the electric motor was insufficient to slice plastic into consistent particle sizes. A paper shredder was also attempted, but it could only cut plastic around the thickness of 1.75mm filament before it was overwhelmed and jammed. A granulator machine (Figure 1) was able to cut the material easily, but the resulting particulates were too large and irregular to use in the FGF tool (Figure 2).

Two methods could be used at this point to create particles of a compatible size. One common method is to remelt the particles and extrude them through a filament die. Then the resulting filament can be sliced into more regularly shaped pellets [8][12]. However, this would negate any advantage of using an FGF tool instead of a filament system and would add an additional melting process between each cycle of recycling. Instead, we followed a second method, which is to feed the particles repeatedly through the granulator until they become more uniform. We found that after 6 to 10 cycles of running the parts through the granulator, most granules were the correct size.

After the repeated granulator cycles, the particles were filtered and prepped for use in the FGF tool. For this, a double filtration device was created. The first screen has holes slightly larger than the maximum dimension of compatible pellets. This allows for the parts too large to be separated and granulated again. The second filter has holes slightly smaller than the minimum dimension of compatible pellets to separate particulates that would be too small to be used.

Figure 1. Recycled material after one granulator cycle (left) next to standardized pellets (right).

Once the granules were sorted, they were placed in a dryer for 8 hours to help eliminate any moisture in the plastic. Printing without drying resulted in discoloration, void formation, and lower tensile strength [19]. Washing the plastic before drying was attempted, but we found no significant effect compared to simply filtering the plastic granules. After initial drying, the granules were placed in a drying cabinet for storage, then placed in a drying hopper prior to print. The plastic particulates sat in the drying hopper for 8 hours at 70 degrees Celsius before printing the material.

Printing: Once the plastic granules were prepared, print extrusion tests of recycled PETG began. The granules were extruded on an AMBIT XTRUDE system mounted on a HAAS TM-2P machining system (Figure 3). Several test prints were done at the identical settings to that of the virgin PETG, but more consistent material flow and deposition occurred with spindle speed and print speed reduced by 10% and temperature raised by about 5 degrees compared to the settings for virgin PETG. All these adjustments were made to optimize the flow of the recycled plastic. Through the slicing software, the part was printed in a continuous motion which slowly raised in the z axis, allowing for no seams in the print and a more homogonous appearing part.

There was an occasional problem that arose where the flow of plastic ebbed due to the plastic granules no longer falling into the chamber where the screw is, so agitating the feed tube regularly was needed to counteract this problem. It is possible that the particulates are locking into place due to the jagged edges and corners found on the granules. This is potentially avoidable if further processing is done to smooth the corners, but no method was explored to discover a way to do so. Another solution would be to have an agitator of some form lightly jostling the material or tube wall, allowing the plastic to fall easily into the tool.

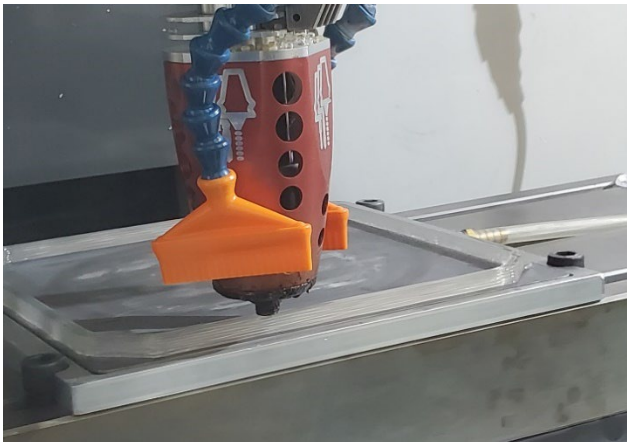

Figure 3. AMBIT XTRUDE FGF tool head in CNC mill.

Parts for cutting tensile samples were printed as shown in Figure 4, where the long sides of the octagon are more than 165 mm in length to allow for variation of part placement in the vise when the machining process occurs. After print completion, they were examined to ensure that no foreign contaminates were found within the walls of the parts.

Figure 4. Recycled PETG print.

Machining and Testing: The last step for creating samples for tensile testing was machining the part. Cuts were made near the very end of the long sides of the samples, leaving as much material as possible (see Figure 5). These straight samples cut into samples by CNC.

The cutting of the samples was done via two CNC programs to match Type 1 dimension specifications per ASTM D638. This was done using a two fluted half inch end mill, using climb cuts to leave the best finish on the part. Climb cuts were selected due to the superior surface finish in comparison to conventional cuts [5]. A modified vise was used to hold the plastic sample upright. This vise has a portion machined to hold the part in both its raw form and to hold the machined portion of the par when it is flipped over to have the part completed. Once the samples were completely machined, they were placed in the drying cabinet to ensure no moisture was introduced. Finally, parts were tested in tension on an Instrom machine and data was collected.

Results and Discussion

The recycled samples were found to have an average tensile strength of 56.00 MPa, with a standard deviation of 1.22 MPa (see Table 1). The virgin plastic material, tested in the same fashion and with the same print orientation, the average tensile strength was found to be 60.06 MPa, exemplifying that there was a 6.76% decrease in overall strength for fully recycled PETG. However, as noted before, the recycled plastic required a 10% decrease in print speed and approximately a 5% increase in print temperature to achieve consistent, optimized flow. These changes must also be acknowledged when considering the difference in material properties.

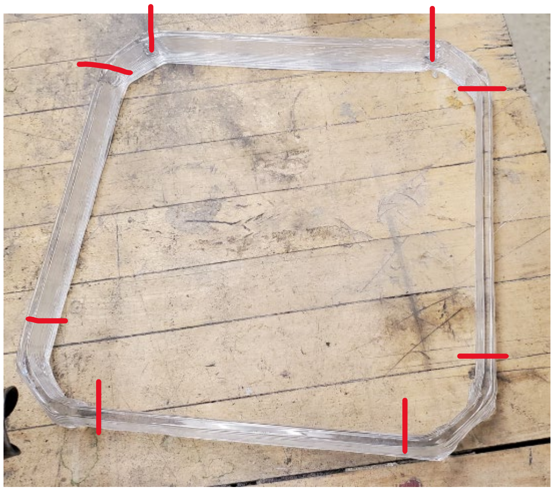

Figure 5. Cut lines for tensile samples.

Table 1. Measured tensile properties.

Material	Ave. Tensile Strength	St. Dev.
100% Recycled PETG	56.00 MPa	1.22 MPa
100% Virgin PETG	60.06 MPa	0.67 MPa

These results were encouraging. Previous research [6] had demonstrated the strength of fully recycled printed parts to be approximately 60% of the original strength of virgin plastic. The more favorable results (93% strength) of this experiment may be due to the adjustments in print speed and temperature. It may also be due to the reduced processing of the plastic; the cited research remelted the plastic between prints to form the new feedstock. However, it should be noted that in a different study analyzing recycling of PETG, there was an increase in the tensile strength on the second and third cycle of recycling [7].

Another possibility for the higher strength could be due to the nature of this manufacturing process. Other studies have been done using filament printers, which tend to have a smaller extrusion diameters and slower deposition rates. It is possible that the larger extrusion pattern allows for better heat transfer between layers, allowing for the plastic between layers to bond to one another slightly better.

Conclusions

As shown in this paper, in-house closed-loop recycling of low friction plastics is possible, and it is a promising avenue for more sustainable LAAM manufacturing. The practicality of the system described here is not yet well optimized for labor and time. However, doing such a process allows for parts with 93% of the strength of virgin plastic in PETG, exceeding the strength of some other additive manufacturing processes.

Potential opportunities of further research stemming from this can branch into a few different directions. Future research could examine the change of properties through successive recycling and reprinting of common polymers in FGF. Another area of study is the effectiveness of different agitators in this process with jagged edged pellets/granules. One other avenue would be research in an improved method for the granulation of plastics that can be utilized immediately for FGF, injection molding, or other plastic-based manufacturing processes. A direct comparison of virgin PETG and fully recycled PETG could also be done using the printing parameters for the fully recycled material to allow for greater understanding of the effects of this recycling method and its direct translation to loss of material properties. Lastly, analysis of the strength between layers of 100% recycled plastic in FGF would also be beneficial to understanding the material's properties.

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