Project Number: ME-JMS-2001

# Reuse Plastic for 3D Printing

A Major Qualifying Project Report
Submitted to the Faculty
of the
WORCESTER POLYTECHNIC INSTITUTE
in partial fulfillment of the requirements for the
Degree of Bachelor of Science
in Mechanical Engineering

by

Yusheng Feng
Aidan Kennedy
Erika Miyajima
Tsuiyee Ng
Sydney Seo

Date: May 13th, 2020

Approved:
Prof. John Sullivan, Major Advisor

# Abstract

Rapid prototyping technology, such as 3D printing, has become an essential part of student projects at Worcester Polytechnic Institute (WPI). Students often print their designs at the Makerspace, located in the Foisie Innovation Studio at WPI. Common printing materials, such as PLA and PETG, are considered difficult to process by a majority of recycling facilities. Presently, the Makerspace does not have an effective means of recycling plastic waste from failed prints or print supports and most ultimately ends up in a landfill. With the social and environmental consequences of plastic pollution as an impetus, the goal of this project was to realize a process capable of rendering 3D printing a more sustainable practice by making use of the waste material inherent in rapid prototyping. To this end, the team constructed a proof-of-concept system that shreds, extrudes, and winds waste PLA into filament for 3D printing. Pursuing a filament diameter of 1.75 mm that is typically observed in commercial filament, the team obtained an average diameter between 1.70 and 1.85 mm and printed satisfactory samples from the recycled filament. The team also developed recommendations for future improvements in this system.

# Acknowledgements

The team would like to thank the help of certain individuals that contributed to the success of the project:

- John Sullivan (faculty advisor), for his guidance and support throughout the project.
- Peter Hefti, for his generous supply of equipment, materials, and access to the MQP lab.
- Ian Anderson and James Loiselle, for their consultation when we were designing and manufacturing our shredder components.
- Torbjorn Bergstrom, for his assistance in constructing our jointer assembly.
- Oluwaseun Oyewole, for his guidance when testing our 3D prints at the Soboyejo Lab.
- Mitra Anand, for his 3D printing advice and recycling information for our research.
- Barbara Furhman, for helping us with purchasing parts.

# Table of Contents

# Table of Figures

# Table of Tables

# 1 Introduction

In the 2013 State of the Union address, former President Barack Obama stated that 3D printing has “the potential to revolutionize the way [people] make almost everything.” Recently, 3D printing has become more affordable and accessible to the general public. While it offers exciting new possibilities for prototyping, the 3D printing revolution has also led to public concerns about how the technology will contribute to plastic pollution (Iowa State, 2020).

Two of the common types of 3D printer filament materials are polylactic acid (PLA) and polyethylene terephthalate (PET). PLA is the most popular type of plastic used for 3D printing. Unfortunately, it is not recyclable by most curbside municipal recycling programs (Iowa State, 2020). According to the American Society of Testing and Materials (ASTM) International Resin Identifier Codes, PLA is categorized as Type 7, or “Other” plastics that are not normally processed by municipal programs. Municipal programs usually recycle PET consumer products but not commercial PET 3D printer filament. PET filament is often polyethylene terephthalate glycol (PETG). The chemical composition of PETG reduces the temperature stability when heated so the material is excluded from common recycling systems (Jones, 2019). However, it is possible to recycle 3D printer filament, regardless of the type of plastic, by remelting and extruding it again without a substantial loss of material (Iowa State, 2020).

Currently, Worcester Polytechnic Institute (WPI) separates 3D printed waste from general recycling but does not have an established system to properly recycle 3D prints. The waste generated from 3D printing eventually goes to landfills (Anand, 2019). This project sought to develop an inexpensive process for recycling 3D printed waste from the WPI campus into printable filament.

During this project, the COVID-19 virus has caused significant disruption to the normal workflow on a national and global scale. As a consequence, many culminating results and data were unattainable within the available working time frame. The results section discloses the results the team was able to collect before the disruption.

# 2 Background

This section addresses the social and environmental impacts of plastic pollution and details the common recycling processes utilized by industries, small businesses, and hobbyists. The common challenges of developing a sustainable plastic recycler and a potential recycler location at Worcester Polytechnic Institute are also identified.

## 2.1 Plastic Pollution

The global production of disposable plastic materials continues to increase rapidly. In the past six decades, mass production has created 8.3 billion metric tons of plastic while the rate of production is faster than the rate of decomposition (Guern, 2018). From the total manufactured plastics, 6.3 billion metric tons have become waste and only 9% have been recycled (Dufour, 2018). Approximately 79% of the plastic produced is piling up in landfills or littering the natural environment, shown in Figure 2.1 (Lashof & Ahuja, 1990). Additionally, approximately 8 million pieces of plastic pollution enter the ocean every day (Surfers Against Sewage, 2019). This has accumulated to 1.8 trillion pieces of plastic floating around the surface of the Great Pacific Garbage Patch in the north-central Pacific Ocean (Lebreton et al., 2018). If current trends continue, there will be approximately 12 billion metric tons of plastic in landfills by 2050. The weight of the accumulated plastic waste would be 35,000 times heavier than the Empire State Building (Dufour, 2018).

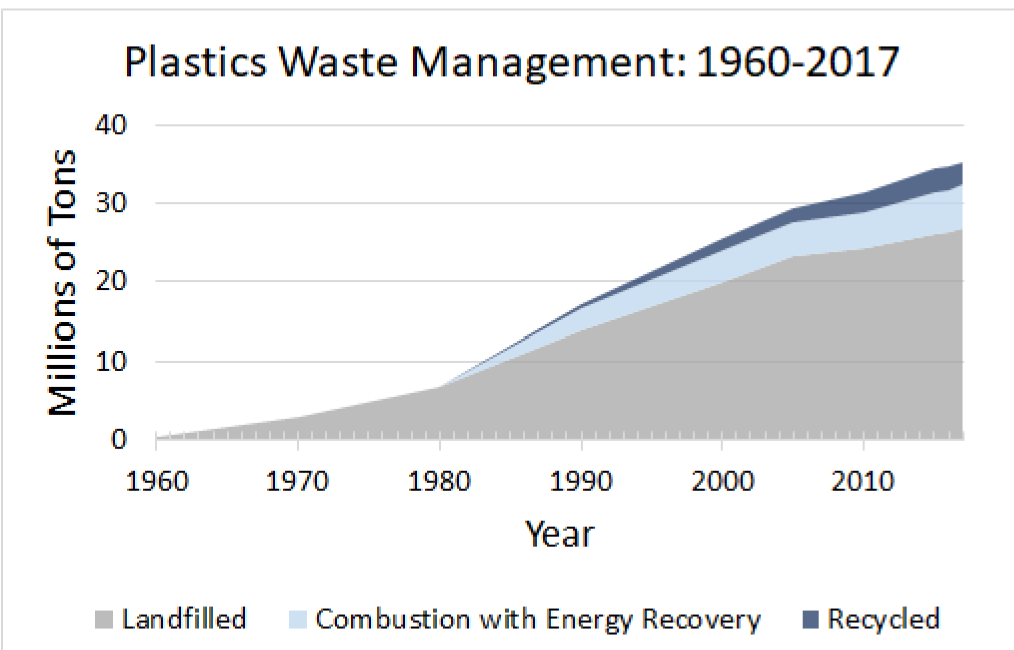


*Figure 2.1: A chart indicating global plastic waste management from 1960 to 2017 (EPA, 2019).*

Since the first use of plastic in mass production, plastic pollution has shown to have harmful health and environmental impacts. From the largest animal to the smallest organism, pollution impacts every ecosystem (Guern, 2018). Aquatic life often mistakes pollutants for food or becomes trapped in plastic waste. These nonbiodegradable substances can block the digestive systems of animals that ingest them, resulting in starvation or death (Madaan, 2016). For humans, exposure to these toxic substances through food or water sources can produce a variety of health problems. Studies show that chemicals from plastic compounds like polybrominated diphenyl ether (PBDE), bisphenol A (BPA), and phthalates can impact the endocrine system and thyroid hormones, leading to cancer, birth defects, immune system suppression, or developmental problems in children (Ecology Center, 2001). Similarly, the environment is negatively affected by plastic pollution. Landfills keep plastics in anaerobic systems where waste materials do not decompose and produce methane. The produced methane is a greenhouse gas that has a global warming potential ten times greater than $CO_2$ (Lashof & Ahuja, 1990). Chemicals from plastics that leak into the surrounding land and water from landfills create significant health implications for nearby plants, people, and animals (Madaan, 2016). Due to these consequences, society has begun focusing on mitigating plastic use and pollution.

### 2.1.1 Polyethylene Terephthalate (PET)

Traditional disposable plastic products are commonly made from polyethylene terephthalate (PET). PET is a lightweight, easily moldable, and strong thermo-polymer resin that is processed from petroleum and natural gas (Vargas, 2009). As a versatile material, PET is the most widely used plastic around the world, ranging from food and beverage packaging to personal care products, pharmaceuticals, and construction materials (PET Resin Association, 2015). While some PET products such as food containers and disposable utensils are non-recyclable, PET bottles and film are often recycled and repurposed into other plastic goods (Subramanian, 2000).

The PET recycling process begins with delivering collected PET plastic containers to a materials recovery facility (MRF) or a plastics intermediate processing facility (IPC) (Hurd, 1997). The quality of PET as it continues through the recycling process determines the value of the post-consumer plastic and its potential to be economically remade into new products. MRFs accept commingled recyclables and separate them into material categories. PET plastic bottles and containers are separated from other recyclables and baled to sell to plastics recycling facilities (PRFs) or reclaimers. IPCs take in plastic bottles and densify them to ship to PRFs, reclaimers, or end-users (NAPCOR, 2018). PRFs are facilities that specialize in baling and grinding. Sorting and grinding are not necessarily enough to prepare PET bottles and containers for remanufacturing; there are many items such as labels, caps, and plastic cups on the bottom of many carbonated beverage bottles (known as “base cups”) that are still physically attached to PET bottles or containers. The bottles and containers require further processing to remove the attached items (Hurd, 1997).

Unlike MRFs and IPCs, PRFs only accept plastic containers, either commingled or separated from other plastic containers. They accept plastics in bundles and sort PET from other plastics by color sorting and granulating PET to ship to reclaimers as ‘dirty’ regrind (Hurd, 1997). Dirty regrind passes through an air classifier to remove materials lighter than PET such as plastic, paper labels, and fines (tiny PET crystallized flakes that are created during the granulation process). A scrubber then washes the flakes with a detergent. This removes any food residue from PET bottles and containers, glues from labels, and dirt from the flakes (Fadlalla, 2010). Once the flakes are clean, they pass through a different particle separation process to extract any excess foreign materials.

Separation technologies include density separation, x-ray separation devices for removing PVC, or optical sorting devices for removing any other contaminants (Bonifazi & Serranti, 2019). The intended applications for the PET flakes will determine the passable PET flake purity level once they are fully refined. After the process is completed, the PET plastic is in a form known as “clean flake”. Reclaimers or converters melt the clean PET flakes into fibers, sheets, or pellets. Finally, the newly recycled materials are sold to end-users to be melted and manufactured into new products (Fadlalla, 2010).

### 2.1.2 Polylactic Acid (PLA)

Polylactic acid (PLA) is more environmentally friendly than PET because it is produced from natural resources outside of petroleum. PLA material is created from plant-based starches such as cornstarch. The PLA market is based around cornstarch since it is abundant and easily accessible (Piemonte, 2011). As a bioplastic, PLA is considered for its compostable properties and has the second largest production volume because of its similar characteristics to polypropylene, polyethylene, and polystyrene (McCauley, 2017; Rogers, 2015). It is often used in a variety of industries, some being the packaging industry for plastic films and packaging, the medical industry for biodegradable medical devices, and the additive manufacturing industry for 3D printing (Rogers, 2015).

PLA has its benefits, but there are limitations. Even though PLA is mainly produced by cornstarch, a lot of corn must be used to create a sufficient amount of material. Not only does PLA production require a lot of resources, but it also takes away what potentially could have been food for consumers (McCauley, 2017). This causes competition for land between bioplastic and food production. According to the Plastic Pollution Coalition, to meet the “growing global demand for bioplastics, more than 3.4 million acres of land—an area larger than Belgium, the Netherlands and Denmark combined—will be needed to grow the crops by 2019” (Cho, 2017). In addition, PLA is expensive. It can be up to 50% more expensive than similar materials because of the complicated process used to convert the starch into the foundations for PLA (Cho, 2017).

Post-consumer PLA can be recycled by composting. PLA waste is generally mixed with other compostable materials while it is being composted because it is biodegradable under industrial aerobic composting conditions (140°F for at least ten days) (Piemonte, 2011).

However, composters realized that PLA does not turn into compost within the desired time frame since it degrades slower than other materials. Due to its slow decomposition, it will eventually produce methane (McCauley, 2017). The methane produced is collected and utilized as fuel. Composting or anaerobic digestion are known as the optimal recycling alternatives for PLA because they allow repurposing of the material into fuel or agriculture feedstock (Piemonte, 2011).

Although PLA is technically recyclable, recycling is currently not commercially feasible and could create issues for current recycling systems. Consumers might unintentionally recycle the material with conventional plastics since it strongly resembles PET and is used for many of the same applications. Due to the low melting point of PLA compared to other plastics, it can "gum-up recycling equipment and contaminate other recyclables" (Royte, 2006). For instance, if PLA commingled with PET, the batch of PET could become contaminated. If that were to happen, then the recycled PET would be rejected and go into landfills. Large-scale recyclers need to remove bioplastics from their incoming materials and that takes more time and money. To minimize these problems, effective consumer education and composting programs are essential to make sure that PLA will not end up contaminating the recycling stream (Royte, 2006).

## 2.2 Plastic Recycling Methods

Encouraged by market demand and environmental regulations, recycling facilities have developed several processes to recover and reuse plastics. Often referred to as mechanical or traditional recycling, the most common practice in the industry is to extrude melted plastic into small pellets. Mechanical recycling is most efficient when working with a single type of material, such as PET water bottles (Popescu, 2018). The recycled pellets, which are then sold to manufacturers as raw materials, serve as a cost-effective and environmental alternative to virgin (newly created) plastics. The pellet form allows the plastic to be easily distributed and used in the production of new parts (Plasgran, 2015). Traditionally recycled pellets suffer from lowered and inconsistent mechanical properties, so the recycled resin is often downcycled into cheaper products (TranPak, 2010). Regardless of their scale, plastic recycling operations generally have in common the steps of sorting, cleaning, resizing, compounding, and spooling, exhibited in Figure 2.2 (Popescu, 2018).

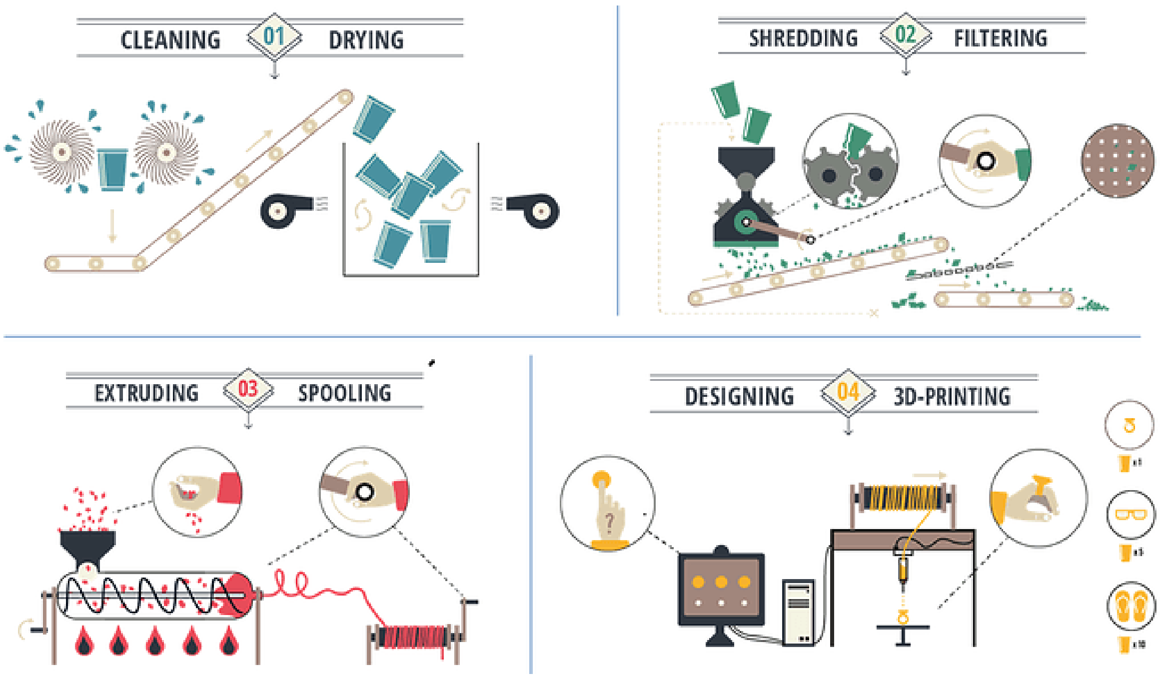


*Figure 2.2: The general recycling process of plastic waste to 3D printing filament (Hallo, 2015).*

In comparison, chemical recycling offers material properties similar to those of the virgin resin. Chemical recycling includes various techniques such as solvolysis, pyrolysis, and gasification (Plastics, 2018). In each process, plastic is broken down into monomers through the aid of enzymes or catalysts (Gerlat, 2018). The solution can be re-polymerized into virgin-quality pellets or further broken down to form a different material. Pyrolysis and gasification also allow the plastic to be refined as fuel for power generation. Although chemical recycling provides a promising new solution to plastics waste, most recycling operations using this process are still kept in pilot facilities due to the process's technical challenges and high initial investment (Laermann, 2019).

## 2.2.1 Sorting

Plastic identification for intact commingled recycled material is based on a standardized coding system. All plastic consumer products are required to feature a Resin Identification Code (RIC) that specifies their basic composition (The Plastic Industry Trade Association, 2015). PET bottles are labeled with RIC 1, which are recyclable in this system, while PLA plastics are labeled with RIC 7, which are not generally recyclable (Gendell, 2017).

Initially sorting base materials whose chemical makeup is known is essential to creating a product of known composition. Different 3D printing materials (e.g. PLA, ABS, PETG) have distinct physical properties and require different design considerations. Often, plastic waste is recycled using separation technologies such as gravity separation, electrostatic separation, magnetic density separation, flotation, or sensor-based sorting (Bonifazi & Serranti, 2019). To describe a few, gravity separation divides materials based on their density properties. For example, mixed particles of polypropylene and PET can separate in air or water because their unique specific gravities cause one material to float and one to sink (PRM Environmental and Recycling Research and Development Institute, 2013). The capability of the float/sink stage to obtain pure material flakes depends on the absence of any other plastics that might also be heavier than water and sink or float with the plastic (Hurd, 1997). In sensor-based sorting, a sorter uses a camera with a visible range spectrometer to detect color and contaminants that are not transparent. An infrared spectrometer is then used to determine various polymer types before a metal sensor can detect foreign particles such as aluminum and iron. For this method, sensors can detect and identify plastic flakes as small as 2 mm (Henry, 2015).

### 2.2.2 Cleaning and Drying

In addition to the base material's plastic grade, the cleanliness of the material is important in ensuring a successful end product. Before compounding, the recycled material must be free of contaminants, including dust, grease, and absorbed moisture. Plastics are ground into flakes and usually cleaned using a water-based mixture to wash off contaminants such as adhesives or food residue (Dvorak, Hopewell, & Kosier, 2009). According to a research article on plastic recycling, newer wash plants use 2-3 cubic meters of water per ton of material. For more innovative technologies, wash plants also use a dry cleaning method to remove contaminants from plastic flakes. Without water, this process uses friction to clean plastic surfaces (Dvorak et al., 2009).

Once the plastic is washed, it has to be properly dried before it is ready for extrusion. When manufacturers recycle plastic, the plastic must have a low level of moisture for peak material performance. For PET, it should be dried to a moisture level of less than 50 ppm (parts per million). To reach this level, the PET must dry for four to six hours at a temperature between 212-248°F (Johnson, 2011). For PLA, it should also be dried to less than 50 ppm. To reach this moisture level, it must dry for two to four hours at an air temperature of approximately 104°F (Henton, 2005). It is recommended that higher temperature levels should be avoided to prevent the materials from discoloring. If the moisture level is not low enough, plastic resins become very sensitive to degradation. This degradation leads to "hydrolysis," the decomposition of the polymer chain and lowering of molecular weight. If the resins hydrolyze, it can clog machines further down the process (Carlson & Capitaine, 2019). Hydrolysis can be reduced by removing moisture through conventional drying methods. Fluid bed dryers, rotary dryers, mechanical (centrifugal) dryers, or hot air dryers are possible methods to dehydrate the plastic before it is resized (Herbold, 2019).

### 2.2.3 Resizing

To heat plastic quickly and evenly inside the extruder for improved workability, waste plastic must first be reduced to small particles. This step, along with sorting and cleaning of the material, can be carried out independently of the extrusion process (Dvorak et al., 2009). For pellet or filament making, pieces are required to have a maximum dimension of 5 mm. There currently exist several commercially available products tailored specifically for this process, including the Filabot Industrial Reclaimer, Filamaker shredders, and several other crowdfunded projects intended for individual consumers (Obudho, 2019). The basic design of most shredders currently on the market follows a similar concept: a high-torque-low-speed power input drives a set of bladed wheels between a complementary set of stationary or rotating blades to shear input plastic into smaller pieces.

### 2.2.4 Compounding and Spooling

After the granulated plastic is fed through a hopper to be melted in an extruder, the extruder pushes the material into a die, whose shape varies with the application of the plastic. For 3D printer filament, the die may be sized to make a 1.75 mm or 3 mm diameter circular extrusion. Since plastics degrade over time and with repeated melting, virgin material is often added to the recycled plastic to maintain its integrity (Dvorak et al., 2009). Due to the exacting dimensional tolerances required for FDM printing, the soft extruded material is tensioned to achieve a consistent cross-sectional profile. After cooling, the filament is wound onto spools and ready to be used for new applications.

Plastic filament is typically functional as long as the created filament can be wound and fed like commercial filament. When the filament is being spooled, it should be wound at a constant tension to ensure a consistent diameter. The diameter should fall within a range of ± 0.02 mm from the nominal value. The larger the deviation, the larger the difference between extrusion volume and the more difficult it will be to get a successful and accurate print (PRUSA, 2019). Filament should also ideally be ductile and have low crystallinity for printability, but small amounts of variation in diameter are acceptable. A sign of potential failure is when discolored sections are found in the produced filament. In this case, the material usually has low ductility and could fracture while printing (Dubashi, 2015).

## 2.3 Companies that Make Recycled Filament

The companies that recycle plastic waste products into 3D printing filament include Refil, Fila-cycle, Filamentive, and Neflatek. These companies aim to make filaments from plastic waste so customers can use their 3D printers in a more environmentally friendly way. The filaments they make include PET filament from PET bottles and commercial waste (Refil, n.d.), PLA filament from yogurt cups (Fila-cycle, 2015), and HIPS filaments from recycled window frames and thermoformed sheets (Nefilatek, 2019). Each company has a unique method of making high-quality filament that is comparable to filaments made from virgin plastics.

When Refil produces their PET filament, they mix approximately 10% virgin PET at the melting process to obtain the necessary filament quality. The PLA and ABS filaments are 100% recycled. They ensure proper filtration of any contaminants from the shredded material before entering the melting process. All of the materials Refil uses are REACH and RoHS compliant (Refil, n.d.). RoHS stands for Restriction of Hazardous Substances and follows the directive by not using six different types of hazardous material that is often seen when manufacturing products from electronic and electrical parts. REACH is an acronym for Registration, Evaluation, Authorization, and Restriction of Chemical. It is a European Union regulation that requires communication between the customer and the manufacturer to inform the customer of chemical substances that can impact their health or environment (Vista Industrial Products, Inc., 2018). Having RoHS and REACH certification enables Refil to understand the composition of the material and the source of the waste for recycling.

Fila-cycle assures the industrial waste they use is clean and low-contaminant. They have tested each material to ensure good quality and have successfully made all of their filaments from 100% recycled plastics (Fila-cycle, 2015).

Filamentive guarantees that the filament they manufacture has a high percentage of recycled material while adhering to BS EN ISO 14021:2016, an international standard for self-declared environmental claims. This standard includes a process where the selected claims are evaluated and verified. To ensure quality filament, they also verify the material they use is coming from a consistent waste source that includes post-consumer and post-industrial waste. Filamentive inspects their filament diameters with a 2-axes laser detector. Visual inspection is also performed before it is individually spooled. The filament is then tested on a 3D printer to ensure quality for each bulk of recycled spools. These extra steps have made a significant difference in quality, as they have managed to retain significant mechanical properties, maintain a set tolerance of ± 0.05 mm for the filament diameter, as well as construct the roundness of the filament to be a minimum of 95% (Filamentive, 2019).

Nefilatek is another company that is also helping mitigate plastic pollution's effect on the environment. When failed prints or waste are made from 3D printing, the waste cycles back into the plastic cycle when they are sent to Nefilatek to become new filament for printing. Nefilatek uses Filabot, a 3D printing filament extruder, to make their filament (Nefilatek, 2019).

Unfortunately, most companies and organizations that have means of turning waste into filament do not have open-source instructions on how they make these recycled filaments. Given the high-quality filament produced by companies, it is believed that the extra steps taken in manufacturing for recycling filament are important in producing high-quality products.

## 2.4 Hobbyists that Recycle Plastics

In addition to companies that are recycling plastics to make filaments, it is not uncommon for hobbyists and amateurs to make personal recyclers. They have unique techniques to meet the industrial standards that can be difficult to attain in regular households.

For the shredding process, people use food mixers, paper shredders, or even homemade low-budget shredders from open-source blueprints from projects such as Precious Plastic (Precious Plastic, 2016). The plastics are usually thrown into a simple sifter to separate plastics larger than 5 mm x 5 mm from the smaller ones (CNC Kitchen, 2018). The bigger ones are shredded again until they meet the specification. Many hobbyist shredders include a sieve at the output of the machine, where shredded plastic can either fall through or be recirculated into the shredder to produce a finer particle size (Precious Plastic, 2016). Some extruding machines also come with built-in grinders, as seen in the desktop filament extruder Protocycle, which offers a complete extruder system that is ideal for production and research laboratories (ReDeTec, 2019). For the drying process, oven drying at the lowest temperature settings or buying a food dehydrator is common. This step is crucial to make high-quality filament, as the moisture of the plastics can seriously affect the outcome of the filament (CNC Kitchen, 2018). For the extrusion process, it is common for people to buy inexpensive kits or make their extruders from open-source options such as the Filastruder Kit, Ian McMill DIY Extruder, Lyman Extruder, and Recyclebot. Making a machine has advantages when producing filament from waste plastic, as users can control and modify it accordingly depending on the properties of the plastics (Kerns, 2018). Typically, an auger screw is used to push plastic through a pipe with a controlled heat source (All3DP, 2019). Many hobbyists also attach filtered nozzles to the end of the extruder. This is important for extruding recycled plastics, as it can filter dirt or debris that would make uneven filament capable of clogging a 3D printer (Filastruder, 2019). It is also common to mix virgin pellets to make the melted material a smoother consistency and maintain the strength of the plastics (CNC Kitchen, 2018). In industry-level companies, the diameter of the filament is typically controlled by laser micrometers in a closed feedback loop (Make:, 2015). Some hobbyists take a less sophisticated approach and simply change the size of the nozzle hole depending on the needed filament diameter. To ensure consistent diameter, it is common to buy laser detectors to measure the sagging of the filament that changes the tension of the spooling process (Filastruder, 2019). For the cooling process, air drying with fans or water bath cooling is a common method. Finally, for the spooling process, it is common to buy premade kits such as the Filawinder, Filabot, or build an open-source spooler.

## 2.5 Challenges in Recycling Plastic into Filament

As recycling technology develops, some of the biggest issues in trying to close the loop on plastic waste for 3D printing are the recycler costs and the quality of the recycled filament. A significant number of 3D printing consumers use 3D printing outside of a manufacturing environment (Figure 2.3). In a 2018 study, a thousand professional respondents around the world answered a survey to understand the leading uses of 3D printing (Statista, 2018). While prototyping, proof of concept, and production are the leading usages from 30-50%, 3D printing for more amateur purposes such as education, art, and personal use are still a prominent number, ranging from 5-30% (Statista, 2018). For more casual users, professional methods are cost-prohibitive and too complex to be feasible (Kerns, 2018). Existing hobbyists and startup companies have previously made smaller machines for recycling plastics, but most custom-made recyclers are either proof of concept, expensive, or produce sub-par filament.

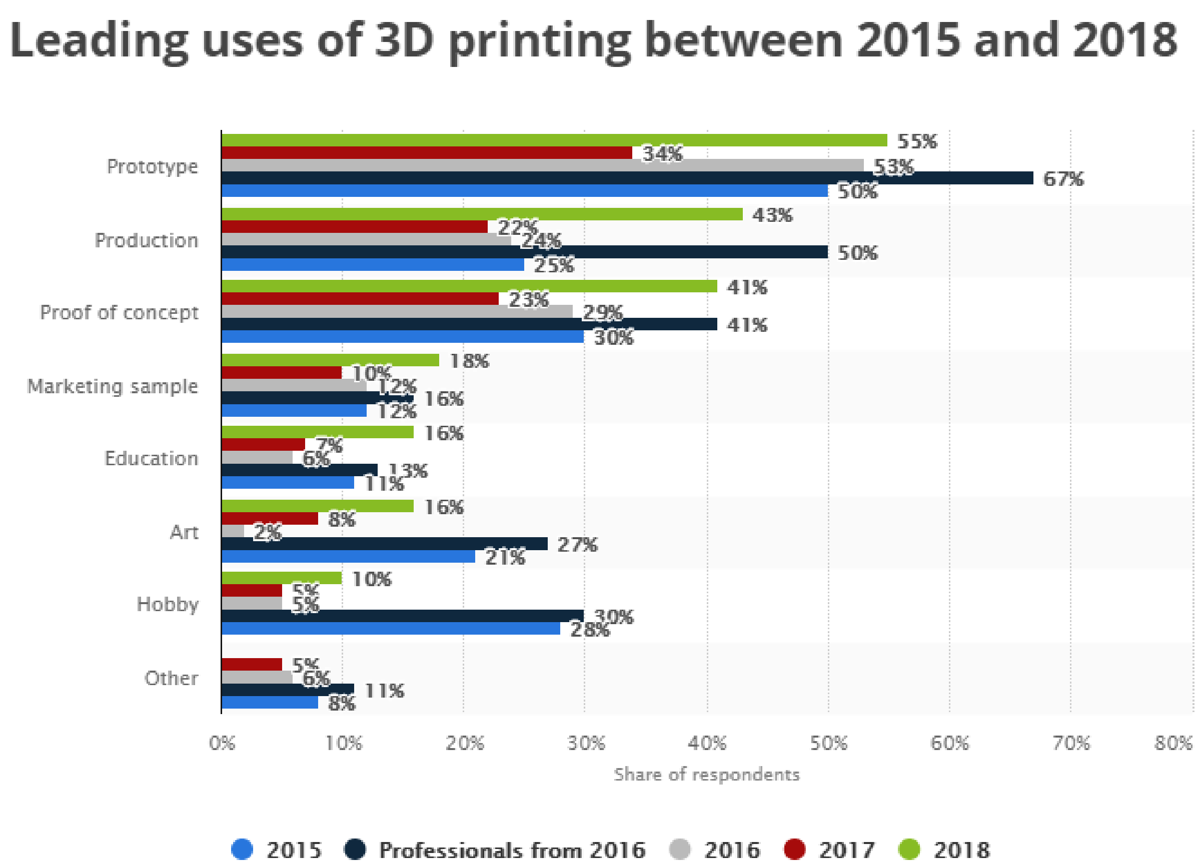


*Figure 2.3: A chart indicating the type of 3D printing usage professionals used from 2015 to 2018.*

Plastic recyclers aren't always cost-effective for consumers to build or buy unless they use a substantial amount of filament (3devo, 2019). Average costs for PET and PLA filament range from $20 to $50 (Flynt, 2017). Based on the extrusion rate, an average recycler needs to run 40 to 90 consecutive hours to pay off its capital cost, shown in Table 2-1. Looking at small to medium-sized recyclers for low-level production, a cost-effectiveness analysis compares popular and successful extruders such as the Filabot EX2 Extruder, FilaFab Extruder, Filastruder, Ian McMill's DIY extruder, Lyman's Extruder, Noztek Pro, and Recyclebot (Obudho, 2019). Since extruder costs constitute a majority of recycler costs, extruder prices are an appropriate representative of the estimated amount needed to make a recycler cost-effective. According to a feasibility study, recyclers have long-term benefits but small businesses and hobbyists do not accumulate waste fast enough to compensate for the work and cost of building and using a recycler (TechforTrade et al., 2016). In comparison to buying materials and building a recycler, buying a new spool of filament with better quality is more convenient.

*Table 2-1: Cost comparison of the hours needed to pay off the capital cost of a filament extruder.*

| **Cost Comparison of Popular Plastic Filament Recyclers** | | | | | |
|---|---|---|---|---|---|
| Machine Name | Capital Cost | Extrusion Speed (kg/hr) | 1 Kg Spools Needed to Pay Off | Hours Needed to Pay Off | Buy or Build? |
| Filabot EX2 Extruder | $2,699 | 1 | 74.97 | 75 | Buy |
| FilaFab Extruder | $920 | 1 | 25.55 | 51 | Buy |
| Filastruder | $299 | 0.125-0.25 | 8.33 | 42 | Buy |
| Ian McMill DIY Extruder | $130-150 | 1 | 4.17 | 4.17 | Build |
| Lyman Extruder | $250-600 | 0.4 | 6.94 | 17.36 | Build |
| Noztek Pro | $1,205 | 0.5 | 33.47 | 66.94 | Buy |
| ProtoCycler | $1,699 | 0.55 | 47.19 | 86 | Buy |
| Recyclebot | $700 | 0.4 | 19.44 | 49 | Buy |

Another challenge in developing recyclers is the quality of filament. In comparison to filaments made from virgin plastic pellets, recycled filaments have weaker mechanical properties (TranPak, 2019). Although recycled filament offers competitive cost and lower environmental impact, diminished material quality remains as a major drawback for consumers. For example, PLA has an average tensile strength of 56.6 MPa and shore hardness of 83D (Lulzbot, 2014). The long-chain structure found in polymers provides desirable properties such as high strength and flexibility. Due to its mechanical properties and printing flexibility, PLA is suitable for many applications like rapid prototyping (All3DP, 2019). When testing with 3D printed specimens made of recycled PLA filament, researcher Isabelle Anderson discovered a 10.9% decrease in tensile strength and a 2.4% decrease in hardness (Anderson, 2017). When recycling plastic, the extrusion process exerts high heat and stress on the material (Lanzotti et al., 2018). The polymer chain structure experiences a large amount of strain and decreases in length each time the material is recycled. As a result, recycled plastic is typically weaker and more brittle than virgin plastic (TranPak, 2019). To retain mechanical properties, some manufacturers blend recycled plastic with its virgin counterpart. Generally, plastic is only recycled two to three times or downcycled for products with lower quality requirements (Sedaghat, 2018). When users 3D print for prototyping or final products, mechanical properties are important for a successful build (FormLabs, 2019). Due to that factor, consumers often pay more money to get better quality filament than use recycled filament (3DSupplyGuys, 2019).

Developing a recycler to attain high-quality filament is complex. Industrial recycling processes use precise equipment and have a controlled environment to make consistent filament for 3D printing. The golden standard in the industry for filament is a diameter tolerance within 0.05 mm and a consistent roundness throughout the filament spool (Bouthillier, 2016; 3D-Fuel, 2019). Small-scaled consumers such as hobbyists that develop their own recycling process often substitute or skip steps, compromising the filament quality. Some mistakes in building a recycler include improper drying methods for the plastic before melting, uneven material extrusion rates, incorrect melting temperatures, inadequate material cooling methods, and insufficient equipment to measure filament diameter (Kerns, 2018). For example, improper drying of plastic before melting could result in filaments with pockets of moisture and air that degrade the mechanical properties (Jamison, 2010). Other factors such as uneven extrusion rates and cooling impact the physical dimensions of the product. Filaments that do not fulfill the dimensional requirements result in clogged 3D printers or low-quality prints from the inconsistencies (Cao, 2017). These mistakes are often due to limitations such as insufficient control over extrusion rates, inadequate components that can withstand a range of temperatures and contamination, incompetent machining experience, limited access to special equipment, and unreliable sources of process observation and control (Kerns, 2018). Although these are common missteps, there are homemade solutions that have shown to be successful since they fulfill the requirements, such as Filastruder and Filabot. These machines have been developed and tested over time, showing that developing a recycler is difficult without engineering experience. As a maturing technology, overcoming these challenges is one of the biggest hurdles in establishing a sustainable 3D printing system.

## 2.6 WPI Makerspace

In Worcester Polytechnic Institute, the Foisie Innovation Studio has a Makerspace area dedicated to 3D printing. Trained students and faculty members have access to Ultimaker, Ultimaker 3 Extended, and Taz 6 Fused Deposition Modeling (FDM) 3D printers. Over the course of an academic year, many users 3D print for academic or personal reasons. Users often print with PLA filament, as it is the most accessible material but materials including ABS, Nylon, Polycarbonate, PETG, and thermoplastic polyurethane are also available for advanced users (Anand, 2019).

The number of 3D prints created throughout the year varies greatly depending on the needs of users (Anand, 2019). In addition, the time of the year is another key factor in how many 3D prints Makespace generates. The amount of prints at the end of a term is normally doubled the number of prints at the beginning of a term (Anand, 2019). That being said, not all of the printed volume will be kept and used as intended. 3D printing can result in failed prints due to printing errors or inadequate model design. From these failures, plastic waste is produced because failed prints are customarily trashed. The amount of waste that is accumulated depends on the volume of each print and when the failures are recognized. The accumulated failure rate can go up to 95% of printed parts (Anand, 2019). Waste is also produced from printed support used to hold the actual model. On average, the makerspace collects approximately two and a half pounds of scrap per week.

The Makerspace currently disposes 3D printed supports and failed prints by storing them in a separate bin from trash and recycling (Anand, 2019). However, since PLA is not considered recyclable by most recycling companies, these prints eventually go to the landfill. Even if a student were to keep the failed prints and supports, these items eventually go to the landfill as well if they are not recycled.

# 3 Design and Methodology

To repurpose waste PLA and PET into filament, five subsidiary processes were developed: shredding, dehydrating, extruding, winding, and testing. This section describes the iterative design cycle and the final state of each process.

## 3.1 Process 1: Plastic Waste Collection and Resizing

### 3.1.1 Collecting Plastic Waste

The first step in this project was to recover plastic waste material. The team collected discarded PLA parts from the Fitzgerald Prototyping Lab in the Foisie Innovation Studio. A team member requested a recycling bin to be set up within the prototyping lab to accumulate scrap PLA parts. Most of the collected PLA parts were printed on Lulzbot TAZ6 or Ultimaker 3 printers. The default settings on the printers were 15% infill at a 210°C extrusion temperature and 20% infill at a 210°C extrusion temperature. The team collected PET bottles by gathering conventional products such as plastic bottles from various recycling locations and additional material from faculty members and students on campus. A sample of these parts is shown in Figure 3.1.

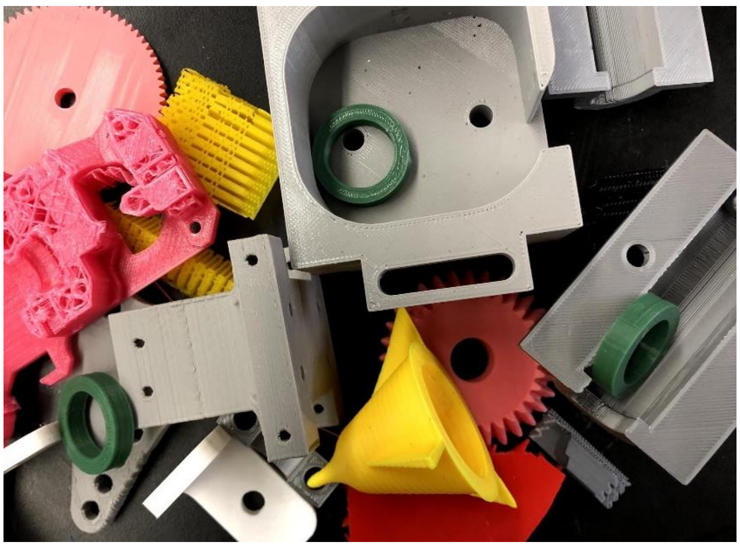

*Figure 3.1: Assorted PLA parts collected on the WPI campus.*

### 3.1.2 Shredder Design Process

The next step was to shred scrap PLA prints and PET bottles to achieve the desired input chip size for the extruder. The team explored several plastic shredding strategies, including shear blades, rasps, handheld planers, and straight-knife jointers. The final two-stage mechanism comprises a straight-knife wood jointer and cross-cut paper shredder in series. The ideation and design process are discussed below.

#### 3.1.2.1 Single/Double-Axle Shear Blades

The team studied common shredding mechanisms for small-scale plastic recycling processes. Specifically, the team was interested in the shredder machine proposed by Precious Plastic, an independent global community fighting against plastic pollution. The Precious Plastic website highlighted two shearing shredder machines with single or double-axle blade layouts, shown below in Figure 3.2. The team adopted the shear blade mechanism and considered developing a similar system, shown in Figure 3.3.

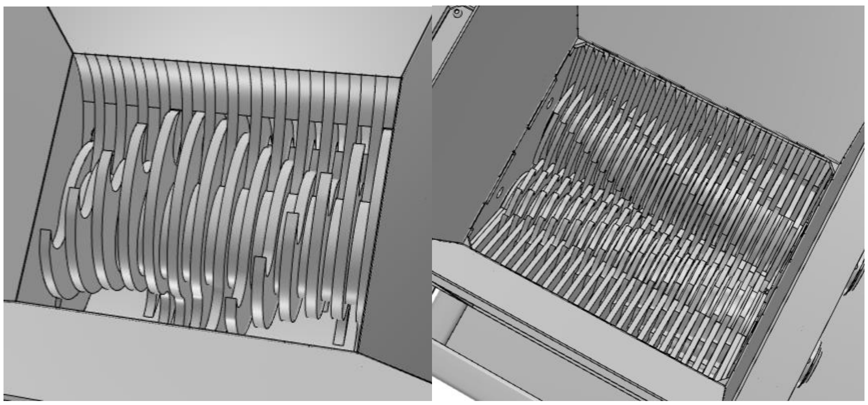

*Figure 3.2: Single-Axle Shear Blades (Left) and Double-Axle Shear Blades (Right) (Shredder Pro Information, 2016).*

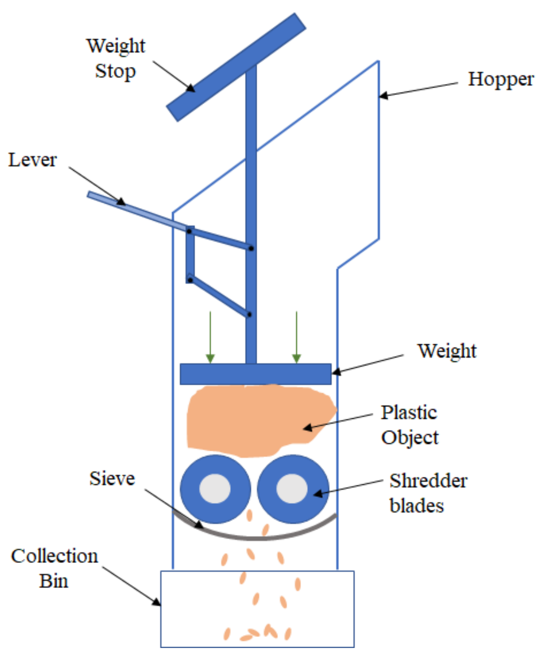


*Figure 3.3: Sketch of shear blade mechanism (not to scale).*

The shredder would push the plastic waste down towards the shear blades by a four-bar linkage. The blades would subsequently grab and pull the input material while breaking it down to smaller fragments. A sieve would be attached below the blades to filter out oversized chips, which could then be recirculated. Precious Plastic proposed a chip geometry categorization demonstrated in Figure 3.4.

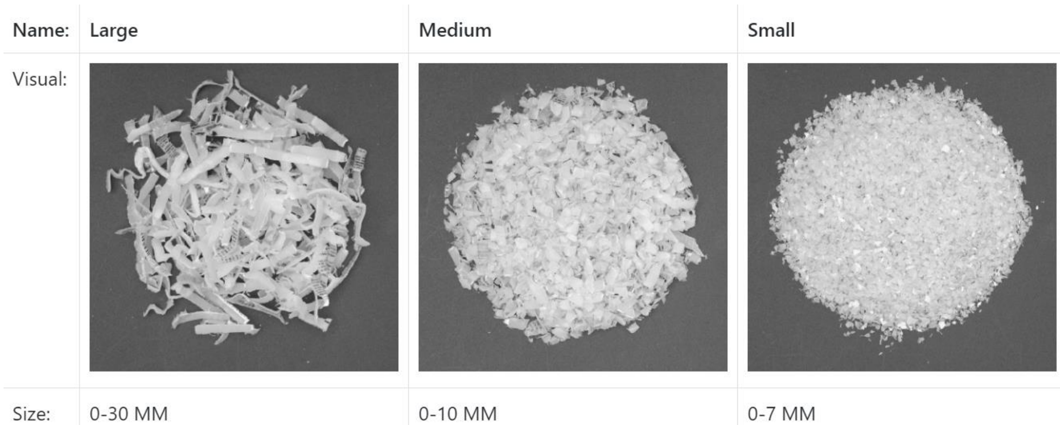


*Figure 3.4: Different classifications of flake size (Shredder Pro Information, 2016).*

Although shear shredder designs are commonly used in large-scale commercial shredding operations, the team chose not to use this mechanism for the shredder. The team did not have access to a power supply with the characteristics recommended by Precious Plastic. There were also concerns regarding the ability of the blades to remove material from parts with smooth geometry. Plastic parts with a smooth surface have a higher chance of floating above the blades rather than engaging with them. Additionally, the team was concerned that excessive amounts of heat generation could occur during operation, causing the plastic to melt and clog the blades. Such an issue would require the team to conduct labor-intensive maintenance.

#### 3.1.2.2 Rasps and Helical Cutterheads

Besides grabbing and pulling input material with shear blades, the team explored a shredder design that would utilize a high-speed rotary rasp to grind off the plastic. The second design included similar features such as the downward plunger and chip filter. Several iterations of the rasp design can be seen in Figure 3.5. To examine the feasibility of the rasp mechanism, a team member conducted preliminary testing with a ⅝-in steel rotary rasp file. Without a hardened edge for the PLA parts to shear against, the rasp could not reliably cut into the parts and generated enough friction to partially melt the plastic.

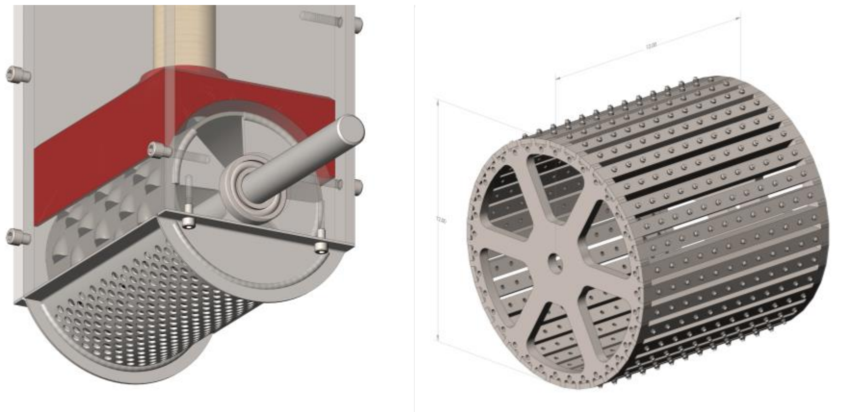

*Figure 3.5: Two iterations of the rasp design.*

After discarding the rasp design, the team explored alternative options, including adopting a helical cutterhead into the second shredder design. The idea was inspired by the spiralized cutterheads commonly used on high-end wood planers. A helical cutterhead features segmented keyholes which can carry a variety of carbide cutting inserts, shown below in Figure 3.6. The team believed the hardened cutting edge would significantly improve shearing capability compared to that of the rasp. The first option was to purchase an off-the-shelf helical cutterhead. The second option was to manufacture a similar workpiece on WPI's campus. To fixture the cutting inserts, the team planned to cut out flat sections and create threaded holes on a cylindrical stock. Such a task would likely require advanced operations on a live tooling lathe or four-axis CNC milling machine. Pursuing either option would require the team to devote a large portion of time and budget in an unproven prototype. The team ultimately decided to investigate more cost-effective mechanisms.

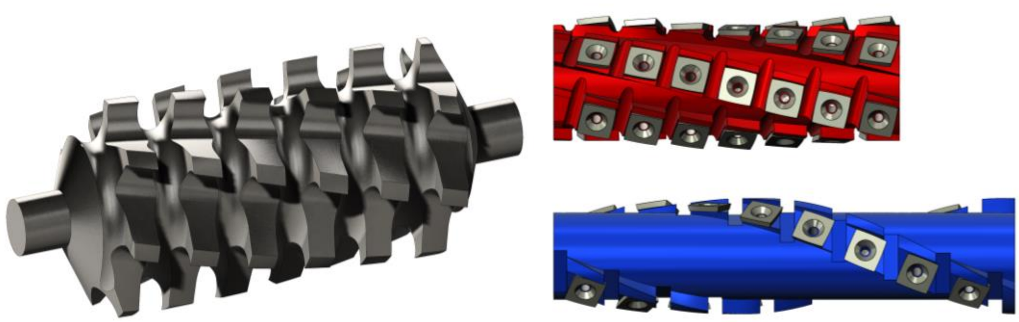

*Figure 3.6: Several iterations of the helical cutterhead design.*

### 3.1.2.3 Handheld Planer

Finally, research showed a potential low-cost solution proposed by joshmt2012 on Instructables Workshop (joshmt2012, 2017). Instead of manufacturing a set of blades, joshmt2012 modified a handheld planer to perform the cutting motion, shown in Figure 3.7. The results showed thin strands of varying lengths of shredded plastic. Inspired by the usage of a handheld planer, the team decided to purchase a used wood jointer to develop a similar shredding mechanism.

*Figure 3.7: Low cost plastic shredder (left) and shredded plastic (right) (joshmt2012, 2017).*

### 3.1.3 Main Components of the Jointer Housing

After purchasing the wood jointer, the team chose to design an enclosure around the jointer to satisfy the functional and safety requirements detailed in Appendix A. The housing of the jointer served to move the plastics parts across the jointer blades while containing the chips within it. For the safety of the operator, the jointer blades were fully enclosed in the housing. The dimensions of the jointer were measured with calipers and tape measures. Once the team developed a prototype design for the housing, all modeling was done on SolidWorks based on those dimensions. The main components of the jointer housing include a baseboard, 80/20 framework, pusher mechanisms, and sidewalls. The design and manufacturing process of each component was completed on SolidWorks and listed in the sequence in the sections below.

#### 3.1.3.1 Baseboard

A team member modeled a baseboard that was placed between the jointer and the jointer stand. The wooden baseboard is larger than the jointer's base to give additional space to fixture the 80/20 framework. They added three holes that would match up to that of the jointer stand so that it could be directly screwed into the jointer without any additional support, as shown in Figure 3.8. A slot was then added on the baseboard directly below the jointer blades to release the chips into the paper shredder. An additional opening was also added underneath the motor for ventilation during operation. As for the manufacturing process, the team laser-cut the baseboard out of ½ in plywood, shown in Figure 3.8.

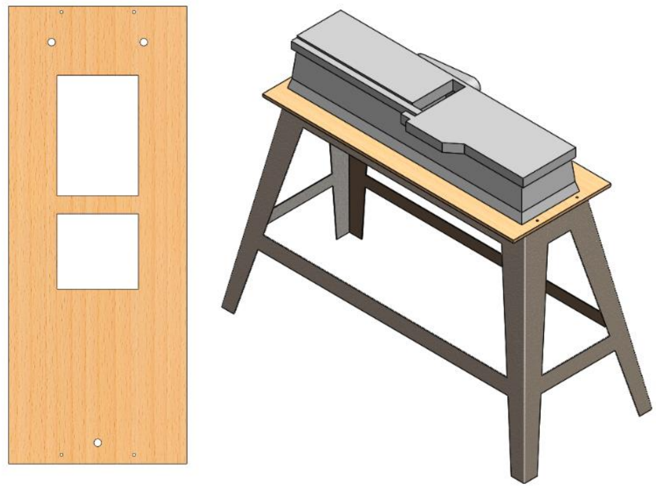

*Figure 3.8: Top view of baseboard (left) and baseboard between jointer and jointer stand (right).*

### 3.1.3.2 80/20 Framework

The 1010 (1 in x 1 in) series of 80/20 was selected for the housing framework. The team modeled twelve pieces of 80/20 T-slot structural aluminum framing with varying lengths. As such, the length of the framework was adjusted to extend over the entire length of the jointer. The width and height of the framework were modeled to contain the 7 in x 7 in pushers. Also, the T-slot allowed the group to easily mount the side walls to provide a complete closure.

For the placement of the 80/20s, four vertical segments of the framework were lined up against the sides of the jointer and sat flush against the baseboard. The four horizontal segments of the framework were then placed to increase the structural integrity of the housing, shown below in Figure 3.9. Finally, the team added four vertical segments to support the hopper. The cross-sectional area of the hopper was designed to allow a maximum input size of 5 in x 5 in x 5 in. To prevent input material from directly falling onto the jointer blades during loading, the team placed the framework of the hopper offset from the blades.

*Figure 3.9: Jointer with 80/20 framing.*

During manufacturing, the team cut the 80/20s into their appropriate lengths with a vertical band saw. The frames were connected via 80/20 fasteners and then attached to the baseboard with L-brackets, shown in Figure 3.10.

*Figure 3.10: 80/20 connectors (left) and 3D printed L-bracket (right).*

### 3.1.3.3 Pusher Mechanism

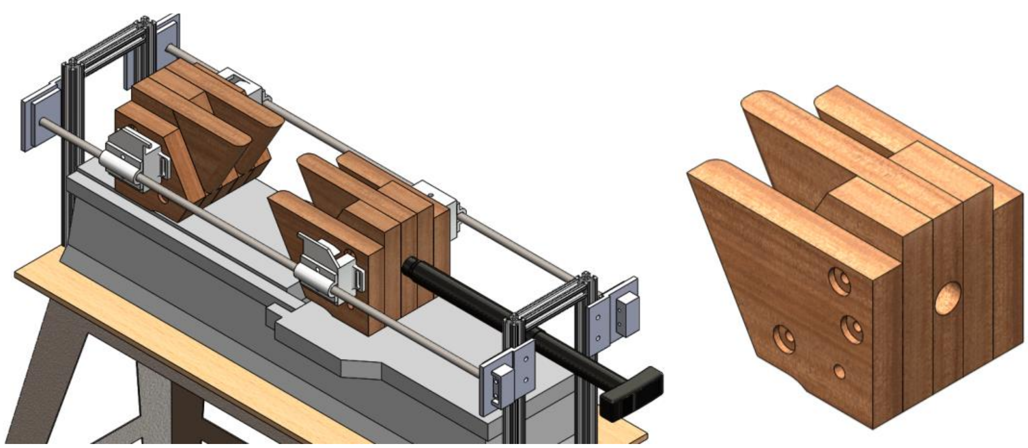

*Figure 3.11: Jointer housing with a pusher mechanism.*

Two pushers were designed to grip and continuously feed the input plastic into the jointer blades as seen in Figure 3.11. A team member modeled each pusher to consist of five sheets of 1½-in thick wood. The pushers were designed to sit flush with the 80/20 framework and angled to compress input towards the blades. The tip of the jointer blades was positioned above the jointer surface, similar to Figure 3.12 below.

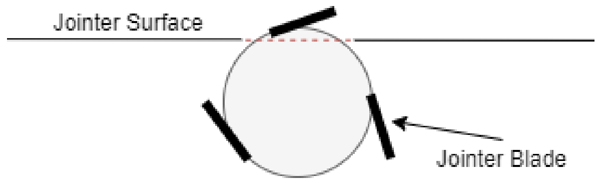


*Figure 3.12: Diagram of side view of jointer.*

To allow the pushers to glide over the blades, the team sanded a groove on the bottom of each pusher. The pushers were given a wedged shape, seen in Figure 3.13, so as the input plastic waste was shredded, the pushers would interlock and push down on the plastic parts towards the blades of the jointer.

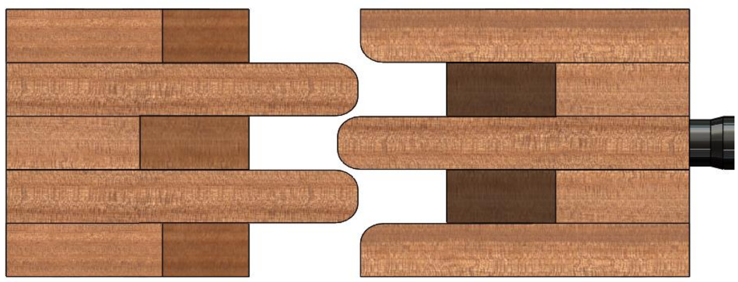

*Figure 3.13: Top view of pushers with interlocking plates.*

The two pushers are held together with two 3.5 lb constant-tension springs attached through 3D printed casings. To allow free movement within the jointer, a pair of steel rods and 3D printed bearing holders hold the ball bearings attached to the pushers as seen in Figure 3.14. In addition to the ball bearings on the sides of the pushers, two transfer bearings, shown in Figure 3.14, were added on the bottom of each pusher to decrease friction.

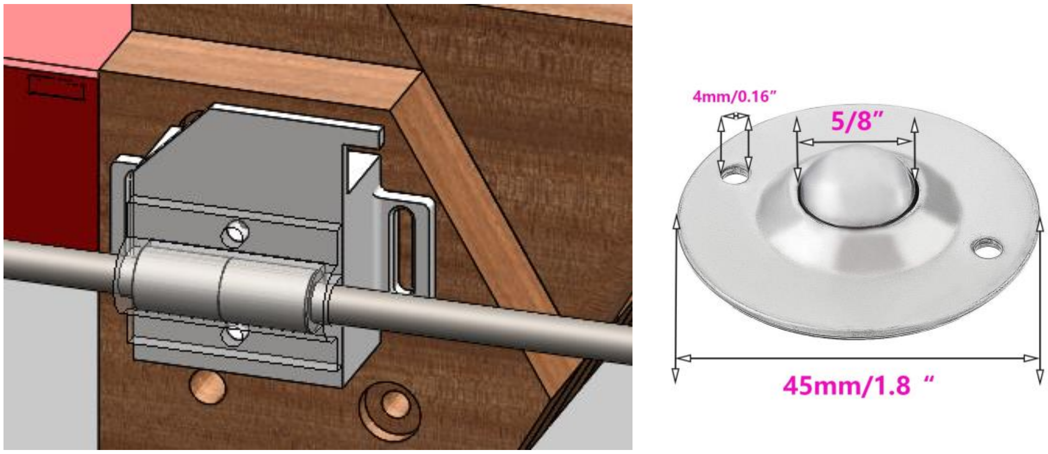


*Figure 3.14: Spring casing (white) and rod-bearing casing (transparent) (left) and transfer bearings and its dimensions (right) (MoKell, 2011).*

The rods were fixtured by the 3D printed supports that were attached to the framework. To prevent the pushers from colliding with the blades, the team also attached two sets of shaft collars on each guide rod to limit the pusher's range of motion as seen in Figure 3.15.

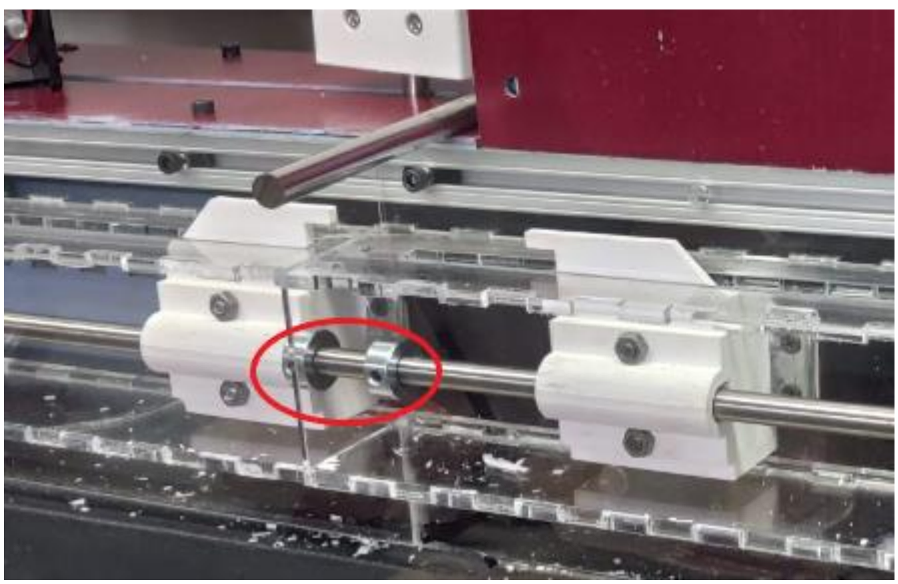

*Figure 3.15: Shaft collars (circled in red) restricted the movement of the pusher assembly.*

In the team's design, the pushers were not identical for functional purposes. The pushers were originally intended to be driven by a motor and belt system. To control the left pusher, a short rod was planned to be inserted into the top surface of the left pusher and fixed to a motor-driven belt. However, due to time constraints, the team decided not to pursue that option. Therefore, the pusher was made to also be manually operated using a handle attached to the right pusher.

During operation, the user would manually pull the right pusher away from the left pusher to open a clearance for loading input plastic. When the right pusher is released, the spring would pull the pushers together and compress the material together. Then, the operator would drive the pushers towards the jointer blades to cut the plastic. When the right pusher reaches the maximum allowed distance set by the shaft collar stop, the operator would drive the pushers across the jointer blade in the opposite direction to make the next cut. The sequence would be repeated until the parts are completely shredded or too small for further processing.

During manufacturing, the pusher plates were cut on a miter saw from 2-in plywood. The team then sanded down the plates to appropriate sizes and thicknesses for assembly. To properly fasten the plates, the team used a drill press to drill through holes for bolt screws to clamp the plates together. Afterward, the group threaded screws and press-fitted wooden dowels in the holes to align the pusher plates. The spring casings and the rod-bearing casings were then 3D printed and attached to the sides of each pusher with wood screws.

#### 3.1.3.4 Sidewalls

To fully enclose the jointer blades and contain the shredded chips, the team modeled birch wood and acrylic boards onto the 80/20 framework. The complete assembly is shown in Figure 3.16. The team used acrylic boards on the front side of the pusher to look inside the housing. Team members created screw holes on all boards to securely connect them to the 80/20 framework. The sidewalls were modeled to cover the 80/20 framework as well as the spring casings of the pushers so the spring casings could easily slide back and forth with minimum resistance. A team member designed the adjacent walls with interlocking edges to improve stability and ease of assembly.

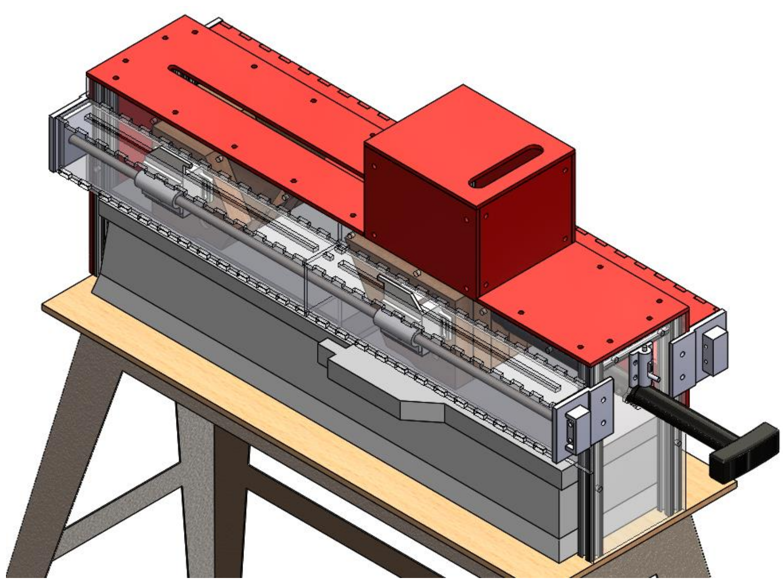

*Figure 3.16: Jointer housing with sidewalls added.*

On the sidewall that is perpendicular to the pusher path, a team member placed a hole for the pusher's handle to smoothly glide in and out. To secure the right pusher when loading input material, two barrel slide bolts were added to the wall to lock the pusher handle in place. Also, when accommodating the initial motor/belt system, a team member included a guide slot to properly align the belt and the pusher path on one of the top walls. Then, a cover was attached to the hopper with a hinge to prevent chips from flying out during operation.

When constructing the walls, the team laser-cut the sidewalls to their appropriate dimensions and glued the interlocking edges together with wood glue or acrylic adhesives. The walls were subsequently attached to the framework with 80/20 fasteners. Below is the team's finished jointer housing.

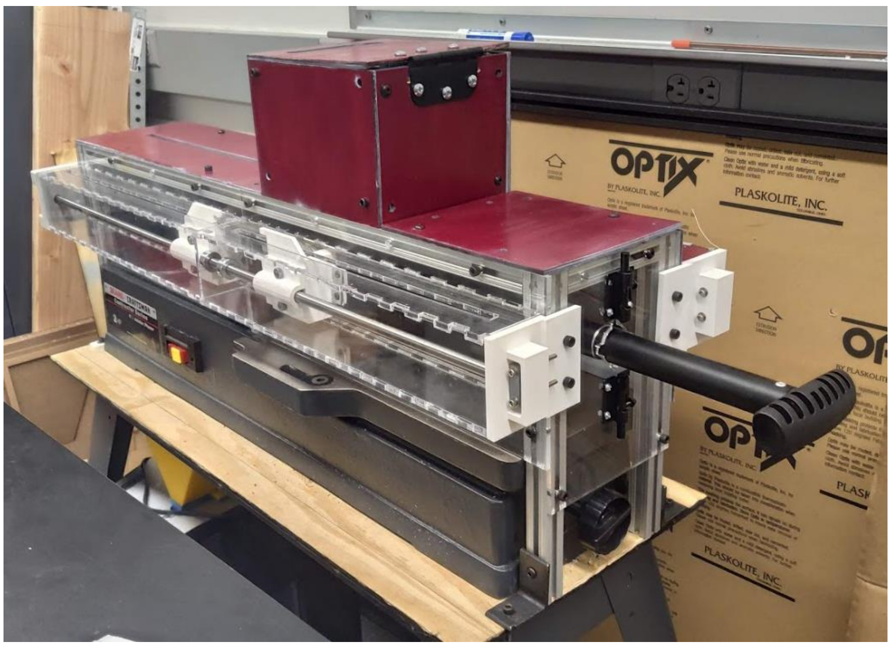


*Figure 3.17: Finished assembly of jointer housing.*

### 3.1.4 Paper Shredder

After the jointer shredded the plastic scrap into small pieces, the plastic was still too large to be properly processed by the extruder. To refine the chips, the team ran the plastic pieces through a micro-cut paper shredder. An average micro-cut paper shredder has a shred size of 5 mm x 13 mm. Despite the shred size being larger than the recommended chip size of the extruder, preliminary testing showed that an unmodified extruder can still extrude filament from 3D prints that have a thin-walled infill structure. Since a paper shredder is easily obtainable and modifiable, the team decided to use a paper shredder as a secondary shredding mechanism.

### 3.1.4.1 Paper Shredder Modifications

After a paper shredder was purchased, a team member removed the paper sensor from the paper shredder. By eliminating the sensor, the paper shredder can run in tandem with the jointer without any delay time. By unplugging the sensor from the shredder circuit, the blades could run forward and in reverse with only the power switch. This modification allowed the paper shredder to continuously process input chips from the jointer.

Next, the team widened the opening of the paper shredder since the original opening was too small for the chips to pass through. Looking at the internal metal gap above the blades of the shredder for reference, the team measured the maximum gap size to make on the lid, shown in Figure 3.18. A member used a rotary tool to cut the plastic lid of the shredder. With a gap that is approximately 4 times bigger than the original opening, more chips can simultaneously fit through without clogging, shown in Figure 3.18.

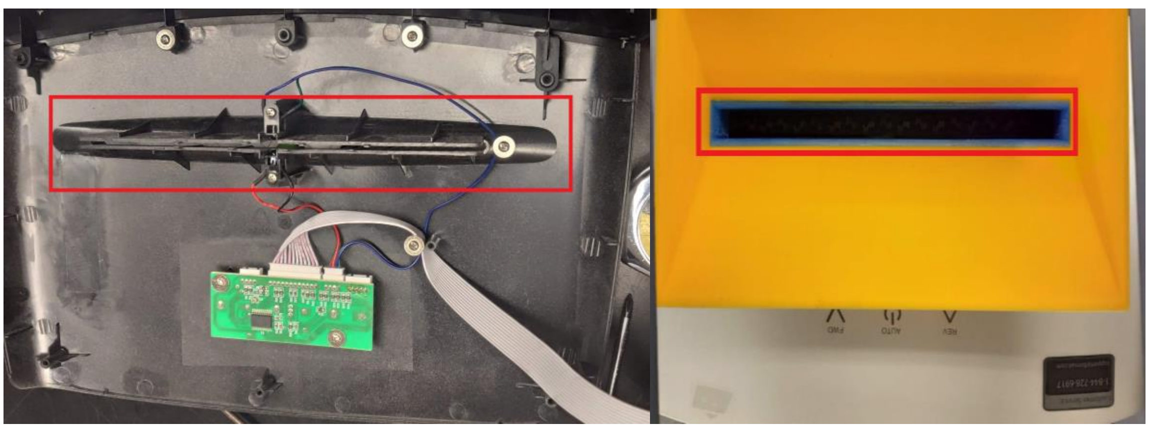

*Figure 3.18: The paper shredder lid before (left) and after (right) widening the slot (highlighted in red).*

A hopper was then added to the opening of the paper shredder so chips from the jointer could fall directly onto the blades. The team made a simple hopper on SolidWorks based on the dimensions of the new paper shredder opening. The team then printed the model on a 3D printer and screwed it onto the shredder lid. Once the team finished modifying the paper shredder, it was placed underneath the shredder so it could work in tandem with the jointer, as shown below in Figure 3.19.

*Figure 3.19: The modified paper shredder (left) sits underneath the jointer blades to catch the falling chips (right).*

## 3.2 Process 2: Dehydration

### 3.2.1 Dehydrating Plastic to Minimize Loss of Quality

After the plastic was shredded, the team decided to dehydrate the chips before they were extruded to avoid extrusion inconsistency from excess moisture. When dehydrating plastic pellets, thermogravimetric analysis (TGA) is ideally performed to quickly dry and accurately measure the chips. A TGA analyzer consists of a precision balance and a sample pan that is found inside a furnace where the temperature can be controlled. In a TGA, the mass of a sample is constantly measured while the temperature gradually changes at a constant rate. For instance, the initial temperature would be 35°C and will increase by 25°C/min while recording its mass until it achieves a final temperature of 1000°C. However, TGA is difficult to perform because it is not easily accessible and is only capable of taking a limited sample size (10.0 mg ± 0.5 mg). Since the team intended to produce a large amount of PLA and PET chips (approximately 1.22 kg) for each extrusion, TGA was not an ideal method to dehydrate the plastic.

A simpler way to dry the plastic chips was to put them in a mesh bag containing a desiccant such as silica gel in a closed environment for a minimum of three to four days. The use of silica gel depends on the humidity of the environment where the plastic chips are stored. The area where the chips were stored consistently had humidity levels of below 50%. If the humidity of the air was at or below 50%, then no moisture would be absorbed into the silica gel. Chips that were extruded without dehydrating did not show any significant difference from the chips that were dehydrated by the silica gel. Therefore, the team decided based on the project environment that it was not necessary to utilize the silica gel.

## 3.3 Process 3: Extrusion to Filament

After the team shredded and dehydrated the PLA and PET scrap, the chips were fed into the Filastruder, a commercially available filament extruder. Similar to industrial extruders, it is intended to process pre-shredded chips or pellets into filament by heating, mixing, and extruding the plastic in a metal barrel, shown in Figure 3.20. The filament then needs to be wound using a separate mechanism to gather the product.

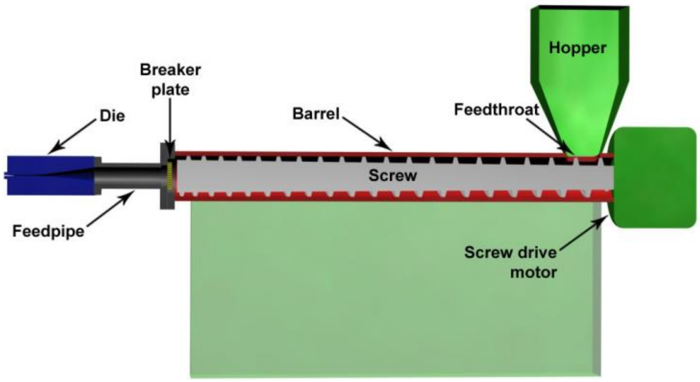


*Figure 3.20: A diagram of an extrusion machine (Mikeeg555, 2006).*

### 3.3.1 Filastruder Assembly and Operation

The team chose to use the Filastruder instead of other market models because of its capability to produce usable filament for multiple materials at a reasonable price. After buying the Filastruder kit, the team assembled the extruder using the given assembly instructions as well as supplemental advice from the Filastruder online community. The assembled Filastruder primarily consists of a hopper, a fiberglass-insulated barrel with a motorized auger screw, a heating element, a machined brass die, and a cooling fan, shown below in Figure 3.21.


*Figure 3.21: The team's assembled Filastruder.*

When the chips in the hopper fall into the barrel, the single rotating screw carries the chips towards the nozzle of the extruder. The heating element on the barrel, along with the rotating screw, heats the plastic through viscous heating until the plastic reaches a malleable state near its melting temperature. By the time it reaches the nozzle, the plastic is at a near-liquid state and the auger screw compresses it through the circular die nozzle to create filament. Immediately after it exits the nozzle, the small fan blows room temperature air at the filament cools and hardens the plastic, shown below in Figure 3.22.

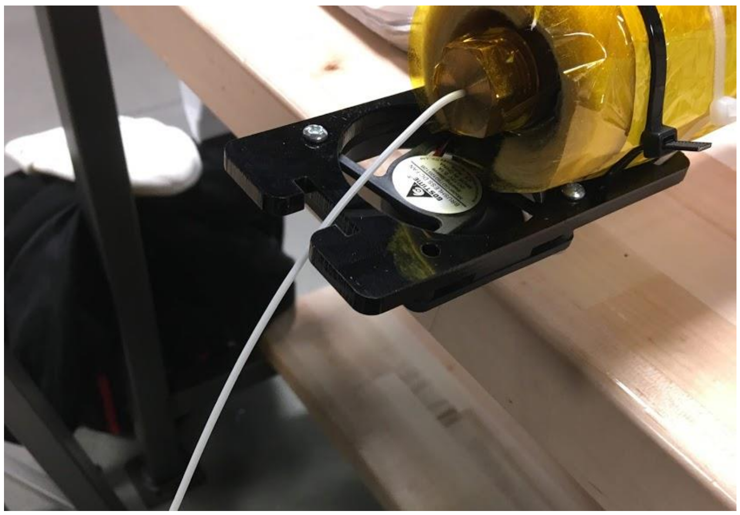

*Figure 3.22: The filastruder extruding ABS filament out of the nozzle made for 1.75 mm filament.*

Before the extruder screw can be run, the heater must be set to the required plastic melting/transition temperature using the extruder's PID temperature controller and remain at that temperature for a minimum of fifteen minutes. The proper heating temperature can vary greatly between extrusion materials. It is often determined using existing empirical data from material data sheets, existing data from extruder users, or experimental data. If the temperature is too high, the plastic will be too liquified to form into filament and can degrade. If the temperature is too low, it will not be able to heat up enough to form into filament and can jam the nozzle and screw inside the barrel. Additionally, the solidified material from a previous run can fuse the inside of the pipe to the auger screw, forcing the pipe to turn with the screw when the motor runs. The result of this condition is shown in Figure 3.23. Once the temperature stabilizes and the extruder finishes preheating, the user can turn the motor on and start inserting chips into the hopper for extrusion.

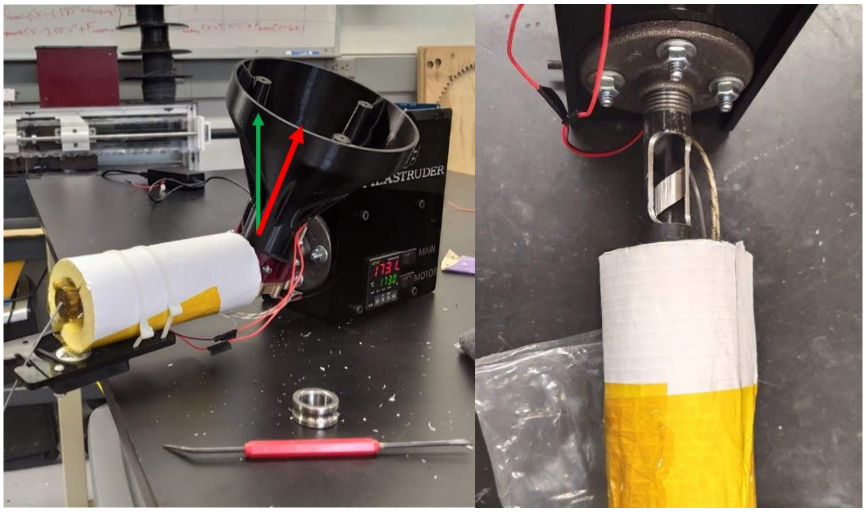

*Figure 3.23: The pipe on the Filastruder can misalign (red arrow) from the vertical position (green arrow) when the screw forces the pipe to turn with it.*

### 3.3.2 Extruder Modifications

When the team first tested the extruder with the ABS pellets that were paired with the extruder, it ran without any complications. Upon testing the chips made from the jointer, the team encountered issues. The first batches of jointer chips were only shredded using the jointer. There was a mix of fine and long chips that caused issues with the extruder hopper, shown in Figure 3.24. With the opening into the extruder dimensioned at ⅝ in x 1½ in, the strands were too large to fall into the auger screw without interference so the chips floated in the hopper. As more chips were added into the hopper, the build-up and entanglement of long strands caused a blockage, shown in Figure 3.24. It was evident that the entangled chips could not be gravity-fed, so the team decided to develop a means of actively forcing chips from the hopper into the extruder.

*Figure 3.24: The long and fine chips that have been shredded through a jointer (above) are tangled and clog the extruder hopper (bottom).*

To start, the group hypothesized that adding a larger and more consistent force or pressure on the chips in the hopper would help the chips flow into the pipe easier. One of the team members designed a motorized Archimedes screw as part of the hopper to carry the chips into the horizontal auger screw in the extruder. The team member 3D printed the screw and attached a motor to the top, shown in Appendix B. While testing, the group found that reasonably small chips could enter the screw when fed in small quantities. When the hopper started to fill with chips, however, the screw did not catch the chips at the top of the hopper and pull them down, seen below in Figure 3.25. The team tried making small modifications to the hopper screw design but these were not successful.

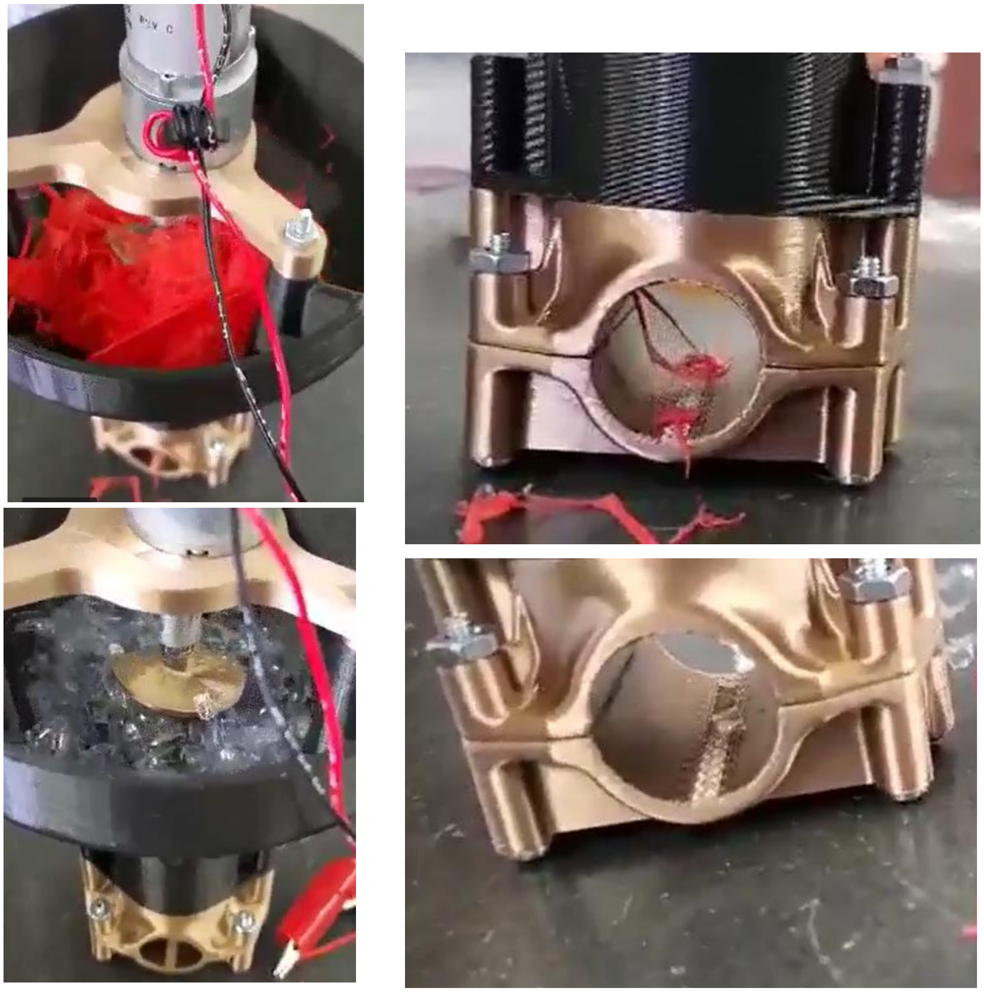

*Figure 3.25: The PLA and PET chips in the full screw (top and bottom left) swirled at the top of the hopper while it did not push anything down (top and bottom right).*

The group then tried a different approach by focusing on chip size. We noticed that the chip sizes we produced varied greatly in two dimensions. The group hypothesized that if we defined the chips to be closer to an industrial pellet size, we might not have a clogging issue. Therefore, the group bought a paper shredder and modified it, as written in Section 3.1.4.1. The resulting chips after being processed by the jointer and the paper shredder were much closer to an ideal chip form, shown in Figure 3.26. The group tested these chips with a normal hopper and found the entangling issue to no longer be a problem.


*Figure 3.26: A sample of chips that have been through the jointer and the paper shredder.*

Another problem arose where chips in the extruder were being caught in the space between the auger screw and the inside pipe. The fit between the inside of the pipe and the auger screw was less than 0.100 in, but it was large enough for the small chips to slide into and jam the extruder, shown in Figure 3.27. When the hopper was full, the jamming caused inconsistent extrusion and stress on the motor. To improve the situation, the team brainstormed a few solutions. The first idea was to remake the inside pipe diameter with a new pipe. A new pipe would have the inside diameter honed to a tighter tolerance for a closer fit. Unfortunately, due to time constraints, the team had to shift to another alternative. The team experimented with a few extrusion process variables to see if the extruder performance would improve, one of them being extrusion temperature. The group tried to raise the temperature of the heating element to increase the preheating and melting zone of the extruder. The team hypothesized increasing the melting zone would reduce the length of pipe the chips could be stuck in. If the chips were stuck between the auger shank and the inside pipe diameter but in the melting zone, the chips could soften enough to shear away.

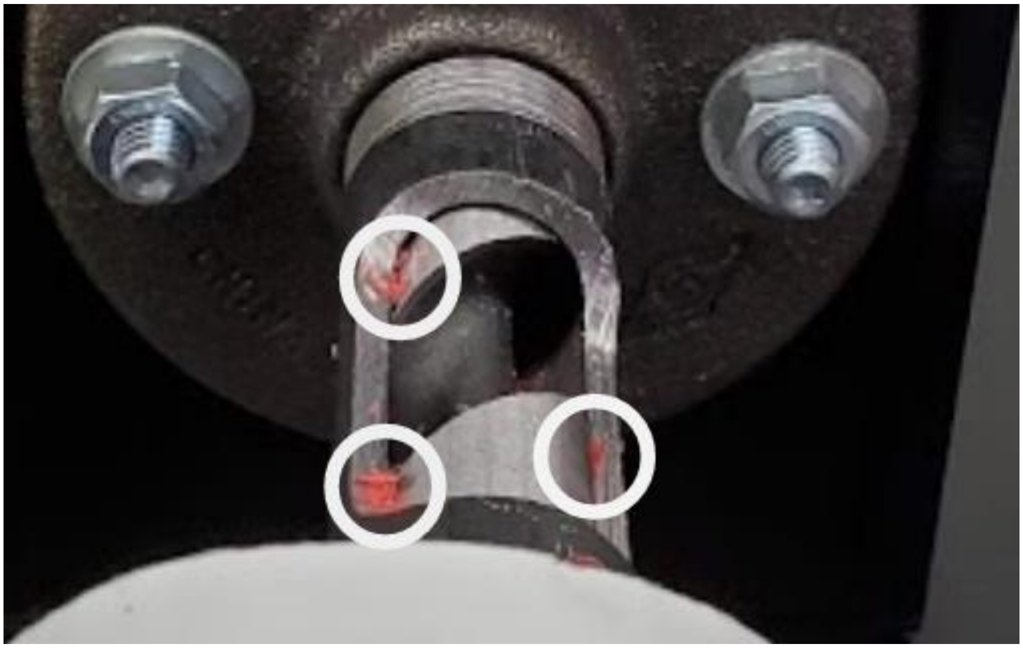

*Figure 3.27: Red PLA chips are caught between the auger screw and pipe at the extruder entrance.*

For both PLA and PET chips, this experiment did not work. The increase in temperature for PLA chips, to avoid jamming within the extruder, negatively impacted the extrusion quality. With a higher temperature, the PLA extrusion could not cool fast enough with the cooling fan, causing the extrusion to warp at the nozzle. When the fan rapidly cooled the PLA extrusion, it was very brittle and had a lumpy and rough surface texture, shown below in Figure 3.28. This quality was not suitable for 3D printing. Thus, increasing the temperature to reduce jamming of the extruding process for PLA chips does not work. On the other hand, PET chips had a different issue. Since PET has a much higher melting temperature than PLA, the extruder had to be set higher than the maximum 230°C temperature of the heating element range for it to melt. When preheating and extruding PET, the team saw issues with the heating element maintaining a consistent temperature. It also had trouble raising the heating to the set temperature so the extrusion resulted in unmelted PET particles with an inconsistent diameter and texture. The team tried extruding PLA again after flushing out the PET filament, but we found the extruder to stop extruding even when an appropriate temperature was set. The team disassembled the extruder and found a large amount of unmelted PET material clogging the nozzle area and the auger screw. With the inability to reach a high enough temperature for extruding and the cause of impediment when extruding PLA, the team decided to solely focus on PLA material.

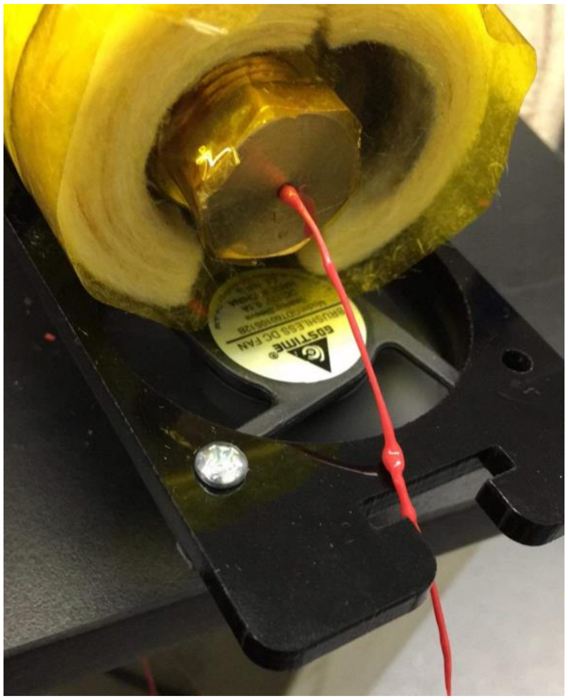

*Figure 3.28: PLA extrusion with a high temperature caused inconsistent extrusion.*

Another variable that the team tested was the feed rate of chips into the hopper. The team manually tested the acceptable amount of chips that could enter the extruder at one time without clogging. A team member dropped different handful sizes of chips into the hopper and found that approximately 10 grams at a time is an acceptable amount. After addressing these issues, the team was able to extrude shredded PLA chips at an appropriate temperature.

## 3.4 Process 4: Spooling the Extruded Filament

To carry out the final stage of the filament recycling process, winding the extruder output onto a filament spool, the team implemented an existing design solution: the FilaWinder, a commercially available hobbyist filament winding machine that was designed specifically to be used with the Filastruder. The team generated initial concepts and part of a custom prototype drawing and spooling system before opting to purchase the FilaWinder. The preliminary designs, as well as the FilaWinder operation, are described in detail below.

### 3.4.1 Design Process

The geometric tolerances of the filament produced by this recycling process are critical to its effectiveness as 3D printer filament. Accordingly, a precise and accurate diameter of the extruder output is paramount in initial functional requirements. In an extrusion process whose input is a nonhomogeneous mix of shards of recycled plastic, which can be reasonably assumed to have subtly different material properties, a truly steady-state extruder output is not guaranteed.

To ensure a consistent output given a well-tuned extruder, the team explored using a feedback controller to actively adjust the tension on the filament based on diameter measurements.

The team's initial plan was to subject the molten extruder output to a continuous tension force, whose value would be modulated by a diameter sensor placed far enough from the extruder nozzle for the filament to have solidified before reaching the sensor. Due to the high cost of commercial optical sensors, the team constructed a rudimentary filament diameter sensor using ball bearings and a precision linear motion potentiometer. The sensor design is shown in Figure 3.29. This sensor would necessitate physical contact and compressive force on the filament since the potentiometer would need to be physically moved by changes in the filament diameter. While this method carries the possibility of slightly deforming the measured filament, which is not desirable, the considerable cost difference between developing this sensor and purchasing a laser micrometer established the linear motion potentiometer as the more cost-effective option. The sensor was to be used in conjunction with a rubberized roller to pull the filament and a filament spool held in constant tension with respect to the roller. This constant tension could be achieved with a current-limited motor and a mainspring.

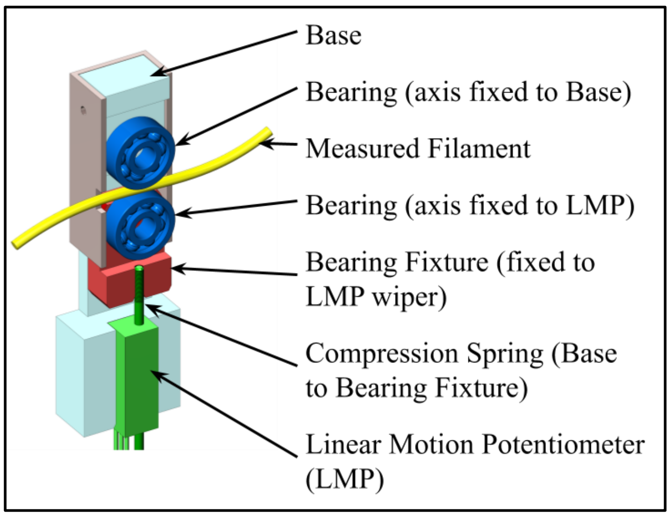


*Figure 3.29: Filament diameter sensor using ball bearings and a precision linear motion potentiometer.*

While controlling the filament diameter with the tensioning system described above would likely produce accurate results, the basic operating principle of this system presented several obstacles in its conceptual design. Sensor delay, caused by the slow rate of the extruder, would make compensating for brief disturbances impossible for the system as designed. Also, protruding contaminants or kinks in the filament due to environmental effects or other factors could either give a misleading value to the sensor or jam the sensor altogether, resulting in plastic buildup at the extruder nozzle. Another issue that would render this method ineffective is the case where the extruder output is already undersized before being drawn. While this issue is potentially serious, it is primarily related to the extruder and not the winding process. The diameter sensor-tensioner design offered the possibility of direct and inline monitoring and control of the filament diameter but presented a significant technical challenge. The problems inherent in this method called into question the system's ability to accurately control the filament diameter. Given the body of simpler and more accessible solutions to the winding challenge that have already been developed, the team explored other means of winding the filament.

Alongside the development of the filament diameter sensor, the team researched an existing prototype winder, the FilaWinder. The FilaWinder and Filastruder are designed and sold by the same company. The FilaWinder, a filament winding system with an integrated sag sensor and filament spooler, was designed to work synchronously with the Filastruder. There is a community of Filastruder and FilaWinder owners whose collective knowledge base includes documentation of the product's assembly, operation, and maintenance. Given the purported advantages of using the FilaWinder rather than developing a new solution, the team purchased a winder. The decision to use the FilaWinder was a compromise that saved the team the development time that creating a novel solution would have entailed and expedited the process of testing the Filastruder as part of a complete filament extrusion and spooling process.

The FilaWinder operates on the principle that if the extruder runs without disturbance, a constant tension from gravity applied to the filament as it is being wound onto a spool will produce a uniformly thick filament. The FilaWinder may be operated in a number of configurations, subject to the user's judgment. The setup used in the team's process had both the extruder and winder sitting horizontally on raised surfaces aligned towards each other and a filament sag sensor in the space between the two, shown in Figure 3.30. The filament is pulled through a PTFE tube to reduce variation in the tension applied to it by the rolling filament spool. The filament is then guided onto the spool through a moving guide slot, whose position is determined by a servomotor and is directly related to the winding speed. The intent of this feature is to produce an even distribution of filament over the full width of the spool.


*Figure 3.30: The team's setup of the Filastruder and Filawinder.*

The sag sensor comprises a laser light source with a cylindrical lens to focus the light into a line and an array of photoresistors. It is designed to hold the lowest point of the filament between the extruder and winder at a constant height so the tension on the filament due to its own weight remains fairly constant. This approach minimizes inconsistencies in the filament drawing process but does not take into account any characteristics of the filament itself. Any change in the output of the extruder is not necessarily addressed by the FilaWinder, and steady-state error in the diameter of the filament must be corrected iteratively by varying extrusion parameters and the distance between the extruder and winder.

Online documentation of the FilaWinder includes instructions on its operation. In order to use the winder, the rightmost and leftmost positions of the filament guide must be set by the user, and the sag sensor must be calibrated for specific use conditions (e.g. ambient lighting). The winder needs several feet of consistent extruded filament to be produced to be fed through the PTFE tube in order to be fixed onto the base of the spool so it can start automatically spooling. Manually creating a consistent length of filament was time-consuming and cumbersome and any kink introduced into the filament during this phase as a result of improper handling required the process to be restarted. Once the filament was attached to the spool and the sensor was calibrated, the winder would run automatically and maintain a constant sag level of the filament.

The FilaWinder is a prototype and its construction presented some issues which required additional attention before the device could be considered operational. As of this writing, the entire frame of the stock FilaWinder is made from laser-cut acrylic with supplemental components available online as stereolithography (STL) files for the buyer to 3D print and assemble themselves. The materials that the team received upon delivery of the product were incomplete and showed no signs of rigorous quality control. The sensor array for the sag sensor was, per the seller’s design, mounted to the face of a sheet of acrylic and set across from the light source such that the light emitted from the laser would reach each photoresistor in the array. However, the sides of the laser-cut frame were not orthogonal to the front and back faces which resulted in significant misalignment. The mounting fixture for the sensor hardware had to be filed down and remounted to ensure that the photoresistors each received light from the laser. The sensor also required an additional shroud around it to reduce light interference. The 3D printed components for supporting the filament spool were replaced as well to solve alignment issues caused by loosely toleranced parts.

## 3.5 Process 5: Mechanical Testing

Once the newly extruded filament was collected, the team performed a series of mechanical tests to measure the properties of the filament. To prepare them, the team constructed models established from the standards placed by the American Society of Testing and Materials (ASTM) on SolidWorks. Each model was exported into STL format and imported into the 3D printer slicer software, PrusaSlicer and Simplify3D, to create the G-code used for printing each specimen type. All of the specimens were printed through the Prusa i3 MK3 and each print had 100% infill density. The team used the Instron Universal testing machine, a servo-hydraulic system, to perform static mechanical tests. To perform the experiments using the Instron, the team used the Bluehill computer software to set the parameters for each of the mechanical tests performed on the samples, shown in Figure 3.31. The team tested for tensile and compression properties.

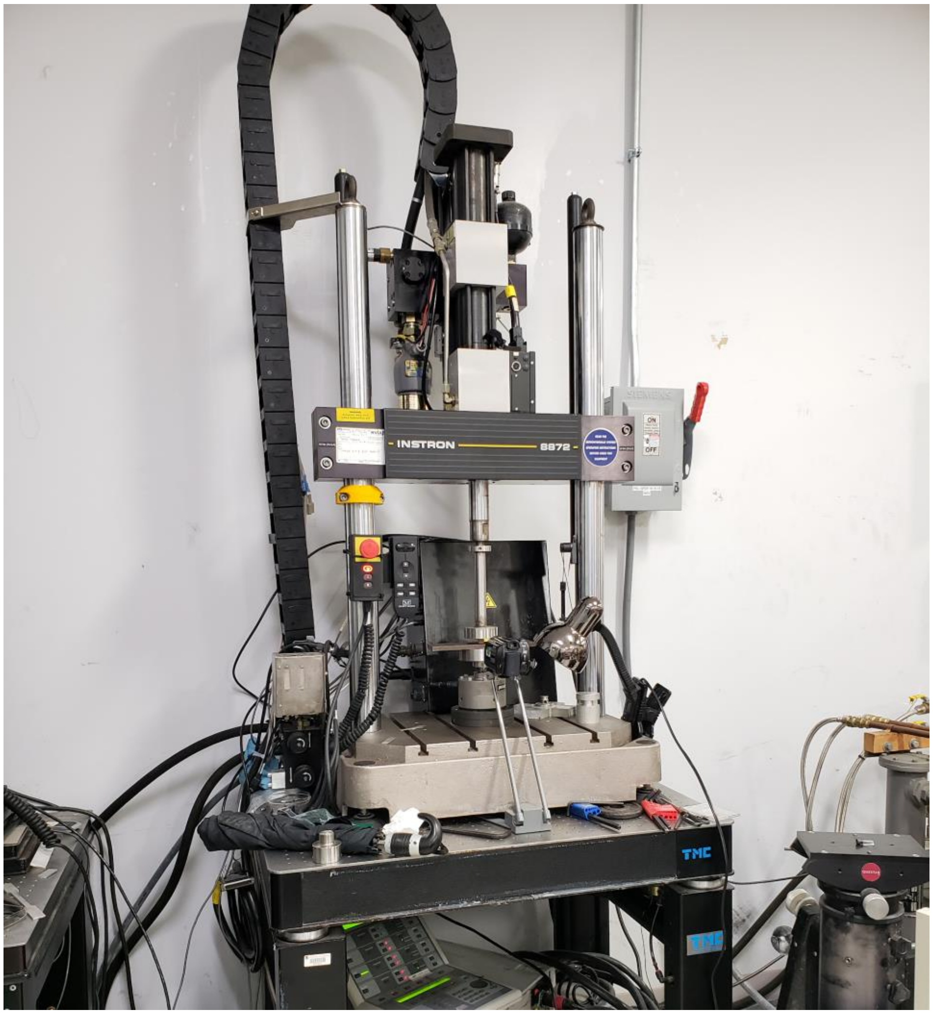


*Figure 3.31: Instron Series 8872.*

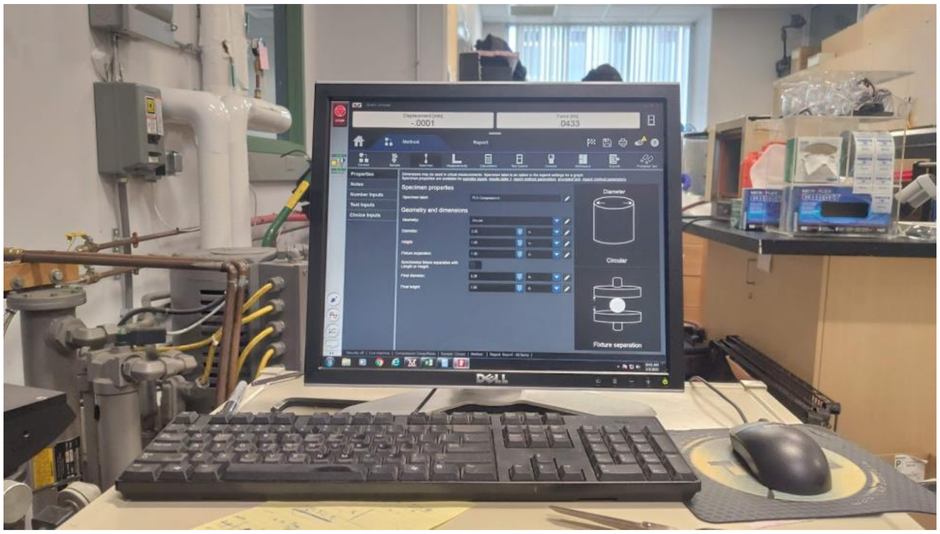

*Figure 3.32: Bluehill Software.*

The compression test provided insight on the behavior of the cellular materials, particularly expanded plastics under compressive loads. Through this test, the team calculated the compressive strength, compressive strain, compressive stress, and elastic modulus. Based on the ASTM D1621 standard, the samples were printed at a thickness of 1 in and with a cross-sectional area of 4 $in^2$, shown in Figure 3.33.

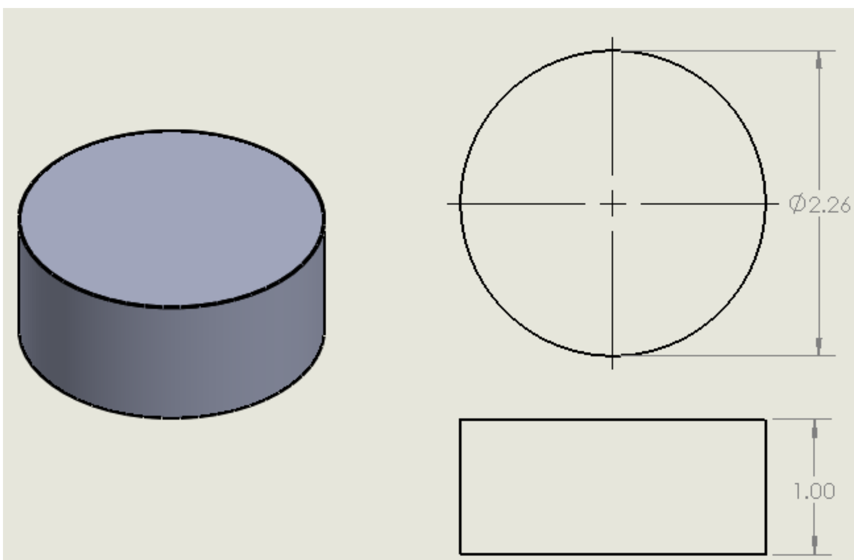


*Figure 3.33: Compression specimen dimensions in inches.*

The other mechanical test that the team performed was a tensile test. For the tensile test, the team 3D printed two sets of samples. One set was printed utilizing commercial filament (HatchBox True Blue 1.75 mm) while the other was printed utilizing the team's extruded filament. Based on the ASTM D638 standard, dogbone samples were printed according to the

Type IV specifications of the sample (ASTM International 2004). The ASTM D638 is one of the most common plastic strength standards utilized to analyze the tensile properties of both unreinforced and reinforced plastics. The dimensions of the dogbone samples used were 115 mm x 19 mm x 3.2 mm, illustrated in Figure 3.34.

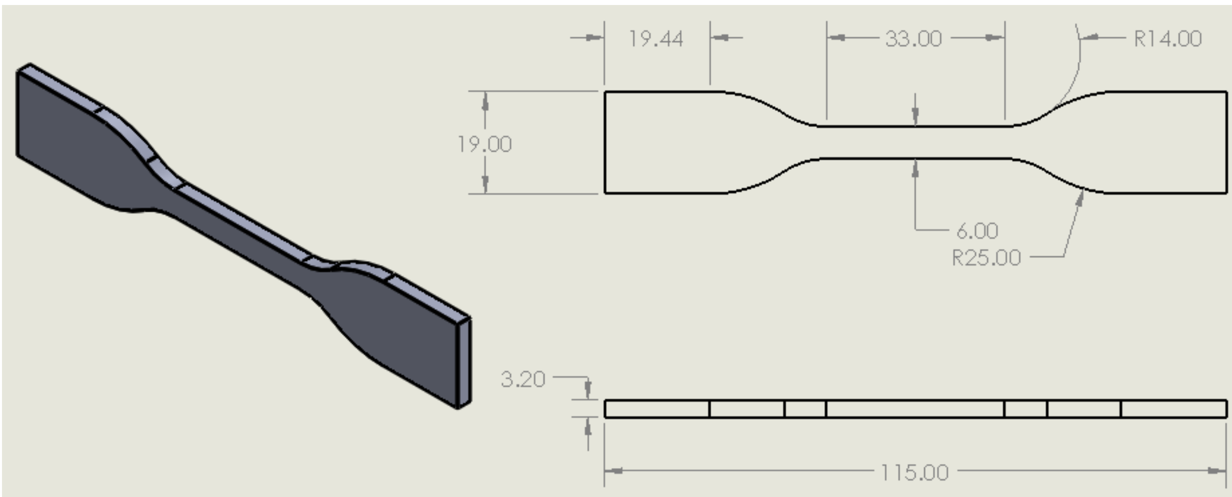


*Figure 3.34: Dogbone Type IV specimen dimensions in millimeters.*

The orientation of the 3D printed specimens affected the results of the experiment. Therefore, two subtypes of samples were also created. One set had a transverse orientation to test the inter-layer adhesion strength of the sample. The other set had a longitudinal orientation to determine the true mechanical stress and strain of the PLA, demonstrated in Appendix E.

# 4 Results and Discussion

## 4.1 Jointer and Paper Shredder Chips

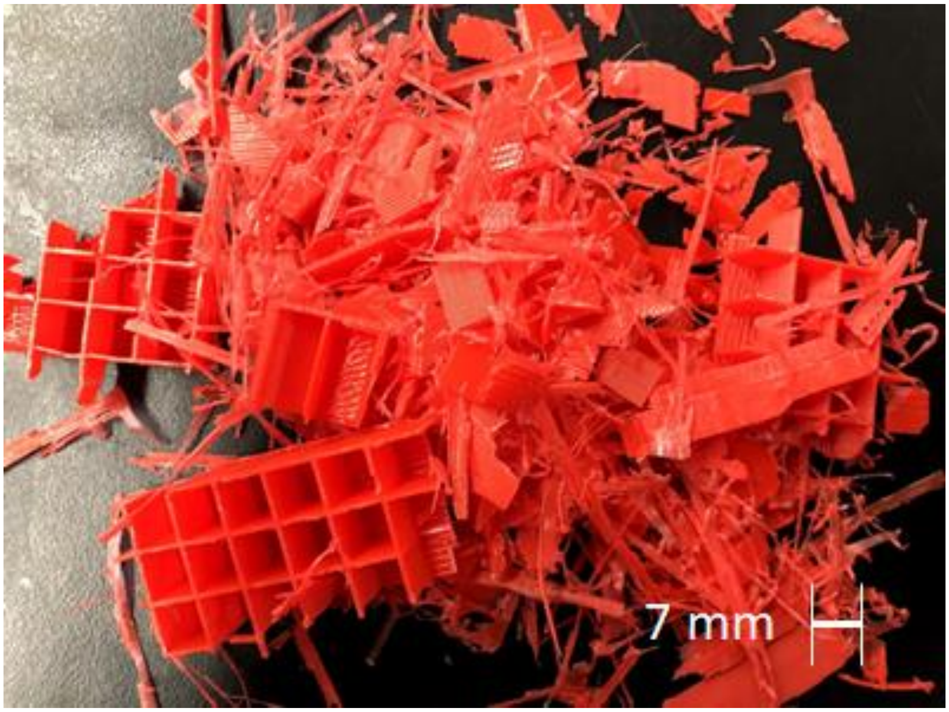


*Figure 4.1: PLA Chips Processed by the Jointer.*

After the input material was shredded on the jointer, the chips were obtained as seen in Figure 4.1 above. The chips that were further processed through the micro paper shredder are shown in the figures below. The team obtained chips that had a wide chip size distribution. The team distributed the chips into three categories based on the chip size and geometry. The first figure shows plastic particles that were significantly smaller than 5 mm, the second figure shows chips that were slightly under 5 mm, and the third figure shows chips that were larger than 5 mm.

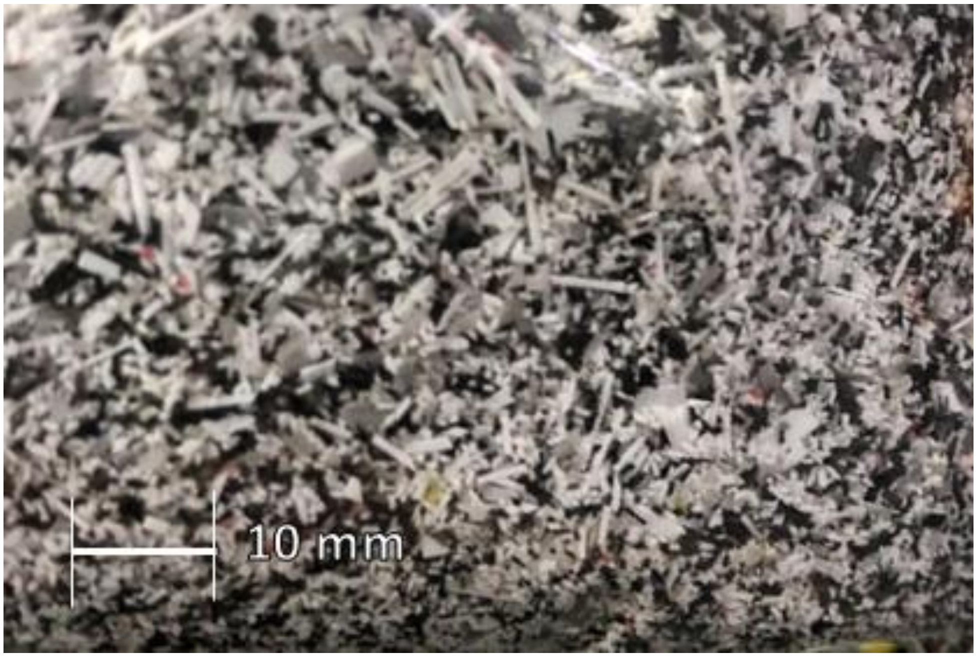


*Figure 4.2: PLA dust particle chips processed by the jointer and the paper shredder.*

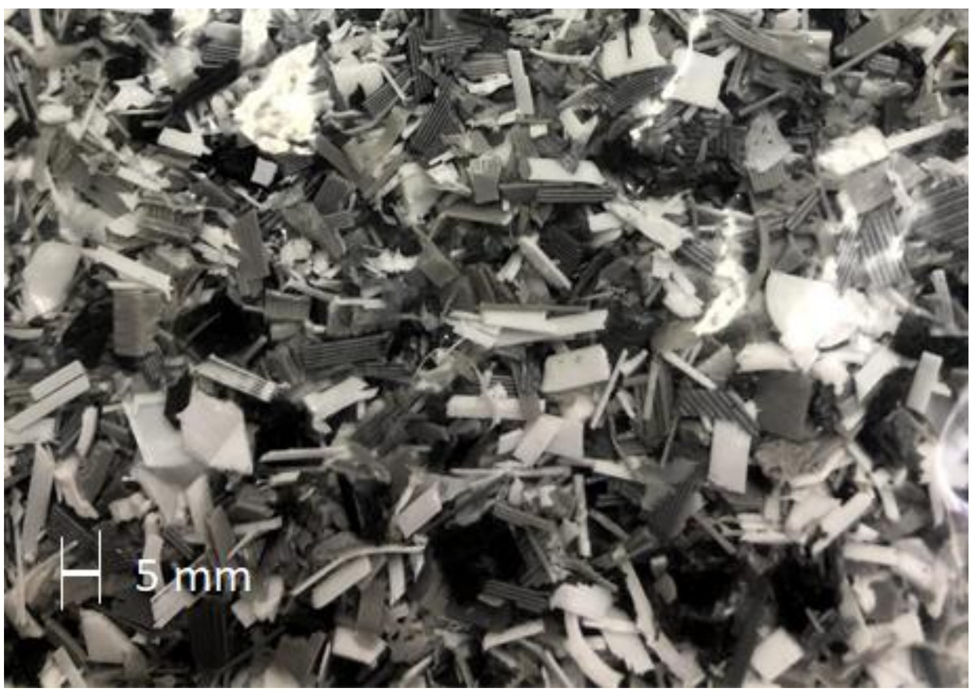


*Figure 4.3: PLA chips smaller than 5 mm processed by the jointer and the paper shredder.*


*Figure 4.4: PLA chips larger than 5 mm processed by the jointer and the paper shredder.*

As seen from Figure 4.4, a portion of the output chips did not meet the functional requirements of being under 5 mm in any dimension. The strands were mainly due to the orientation of the chips entering the paper shredder. When the jointer cut off a long section of the input material, the output might end up with long strands depending on the chip's orientation as it fell into the paper shredder. These strands prevented the extruder's auger screw from compacting the material tightly. Consequently, higher torque was required to shear the large chips at the opening of the extruder. In comparison, the fine chips that went through the 5 mm sieve seen in Figure 4.3 were more suitable for the extrusion process because of its ease of compaction. Although the chip size distribution was wider than initially intended, the majority of the chips were sufficiently small and able to be processed by the extruder.

### 4.1.1 Shredded Chips Discussion

The jointer and the paper shredder fulfilled the key functional requirements proposed earlier in the project. The system was capable of producing solid and unmelted chips by shredding PLA or PET with a standard 110 V power supply. The jointer allowed an input volume up to 6 in x 6 in x 5 in. Both operations functioned properly at room temperature and independently from the other processes. Although additional labor was required to transfer the chips, the independent system would allow continuous operation if subsequent processes were experiencing difficulties. Traditional personal protective equipment was required during operation to guard against exposure to high-frequency sounds from shredding that can damage hearing. Despite most chips being contained within the jointer housing, safety goggles were also worn and are recommended during operation.

Several aspects of the shredding process held significant room for future improvement. The team believes implementing an automated motor/belt system would be highly beneficial to the jointer housing to reduce the amount of manual labor. The pusher plates were also undersized from manufacturing, leaving flying chips from the blades trapped underneath and behind both pushers. Dimensional accuracy of the baseboard and walls could be improved to prevent chips from entering the gaps.

## 4.2 Extruded Filament

From experimentation, the team identified approximate values for extruding parameters to create printable filament. The team defined the parameters to be valid only in the environment that the team has tested the extruder. Other environments such as areas with high humidity are subject to different parameter values for successful extruding. The lab humidity within the duration of this project did not exceed 50%. As such, extrusions above a 50% humidity level are potentially subject to different parameter values. The project was also conducted in a poorly insulated lab with exposure to outside temperatures from the windows. Due to this interference, the ambient air temperature was not an average of 20 to 22°C, but rather ranged from 10°C to 24°C. Based on these environmental conditions, the team found the optimal extruding temperature at 170°C for a smooth extrusion, shown in Figure 4.5. Along with the temperature, the optimal feed rate variable is approximately 10 grams every 3-5 minutes or until the extruder hopper is empty.

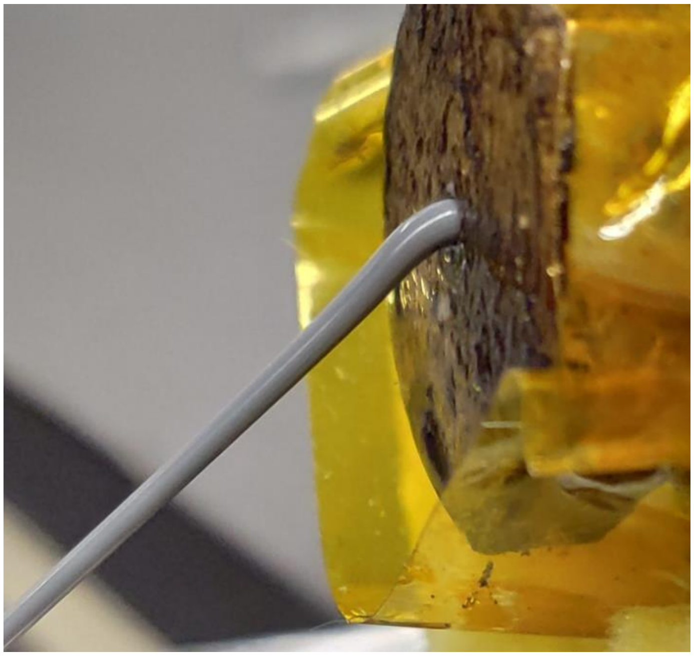

*Figure 4.5: Smooth filament extruded from the brass nozzle.*

### 4.2.1 Filament Diameter and Variance

With the given extrusion parameters and multiple sessions of extrusion, the team measured with digital calipers the diameter of the filament as undersized, ranging from 1.0 mm to 1.7 mm with an average of 1.3 mm, shown below in Figure 4.6 and detailed in Appendix C. To address this outcome, the team drilled the extruder nozzle to expand the 1.61 mm sized hole to a 1.93 mm hole based on the ratio of the extruded filament diameter to the nozzle size.

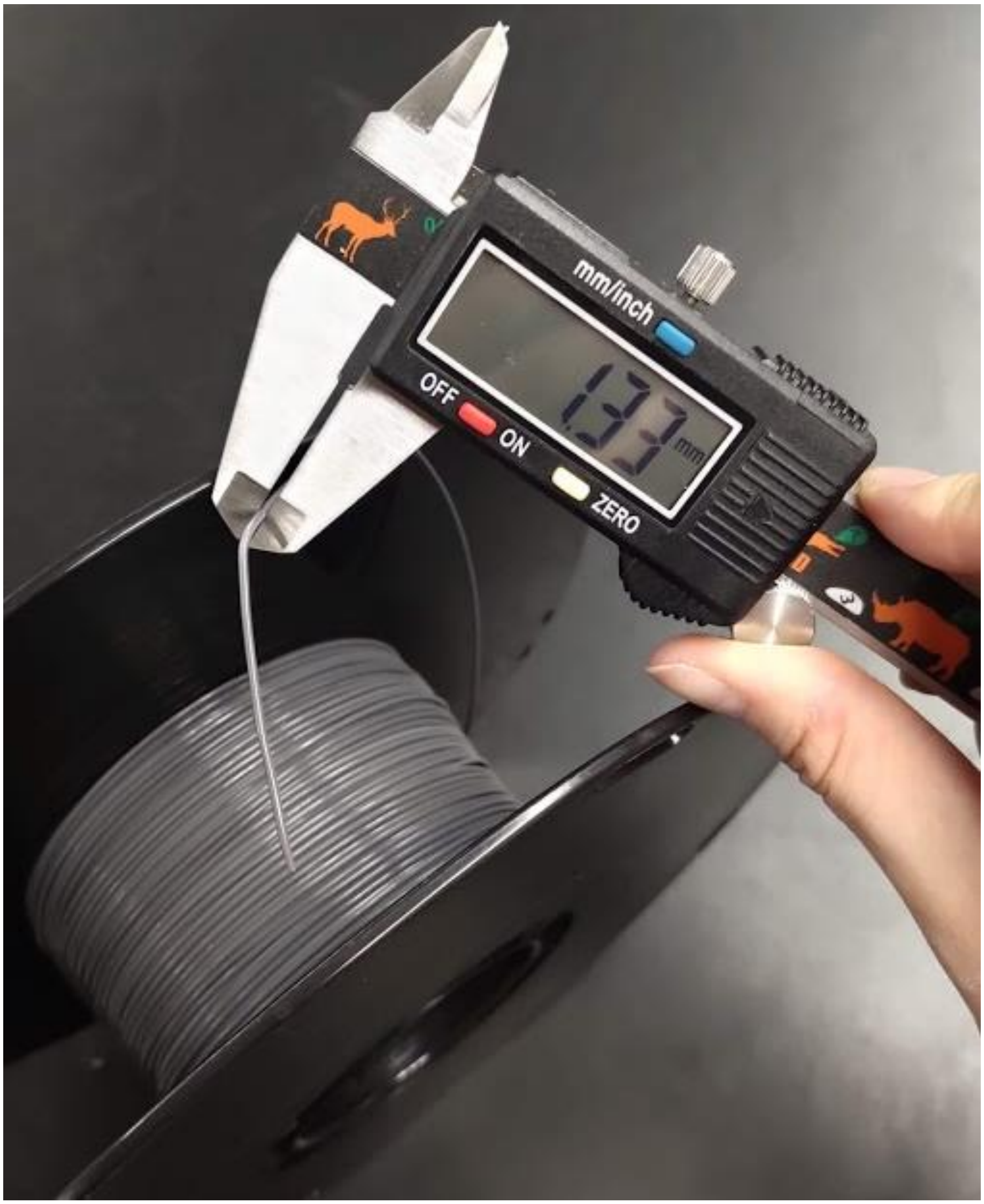


*Figure 4.6: Undersized filament that measured an average diameter of 1.3 mm.*

After enlarging the nozzle, the extruder started extruding filament with an average diameter of 1.7 to 1.85 mm, close to the 1.75 mm diameter of the commercial filament. The team also found that if the filament is extruded to the ground and not wound by a winder, there is a significant diameter variance due to the changes in tension as the filament coils on the ground, shown in Figure 4.7. Recorded from the filament that was pulled by gravity to the ground, the standard deviation of the diameter is 0.1688 mm with a minimum diameter at approximately 1.37 mm and a maximum diameter at approximately 2.23 mm, shown below in Figure 4.7. For the filament that was extruded with the FilaWinder, the diameter was on average 1.85 mm with a standard deviation of 0.107 mm, a minimum of 1.55 mm, and a maximum of 2.12 mm, shown in Figure 4.8. This shows that the winder does help reduce the diameter variation in comparison to an extruder that did not have a winder. The data these numbers were calculated from are listed in Appendix D.

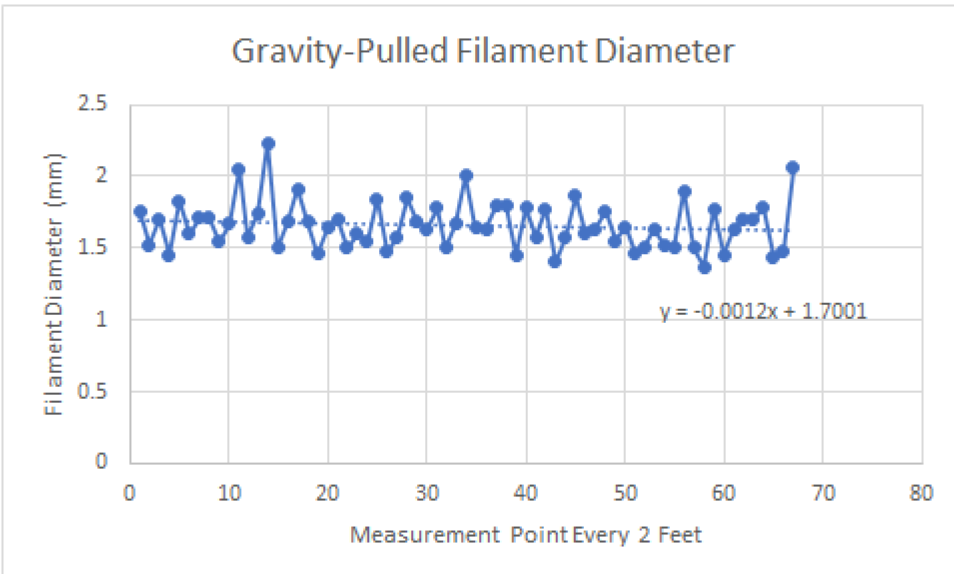


*Figure 4.7: The diameter of gravity-pulled filament over the length of the spool.*

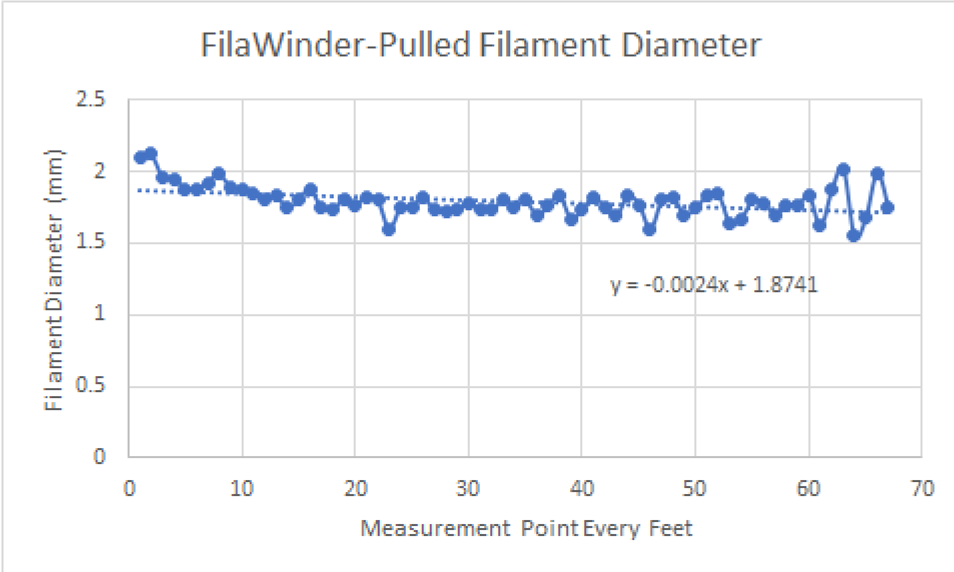


*Figure 4.8: The diameter of FilaWinder-pulled filament over the length of the spool.*

### 4.2.2 Visual Inspection

When visually inspecting and comparing the recycled filament to commercial filament, the team noticed that the recycled filament had a higher gloss than commercial filament, shown below in Figure 4.9. The team also noted that there were visible contaminants within the recycled plastic but it was almost as smooth as the commercial filament. The diameter variance of the filament wound with the winder was also barely visible to the naked eye. The team concluded that based solely on visual inspection, the filament was suitable for 3D printing.

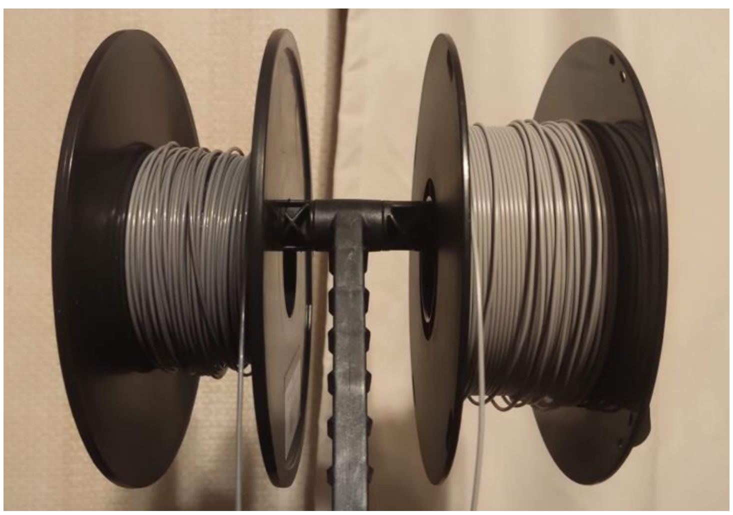

*Figure 4.9: The recycled filament made with the Filastruder and FilaWinder (left) and the commercial filament (right).*

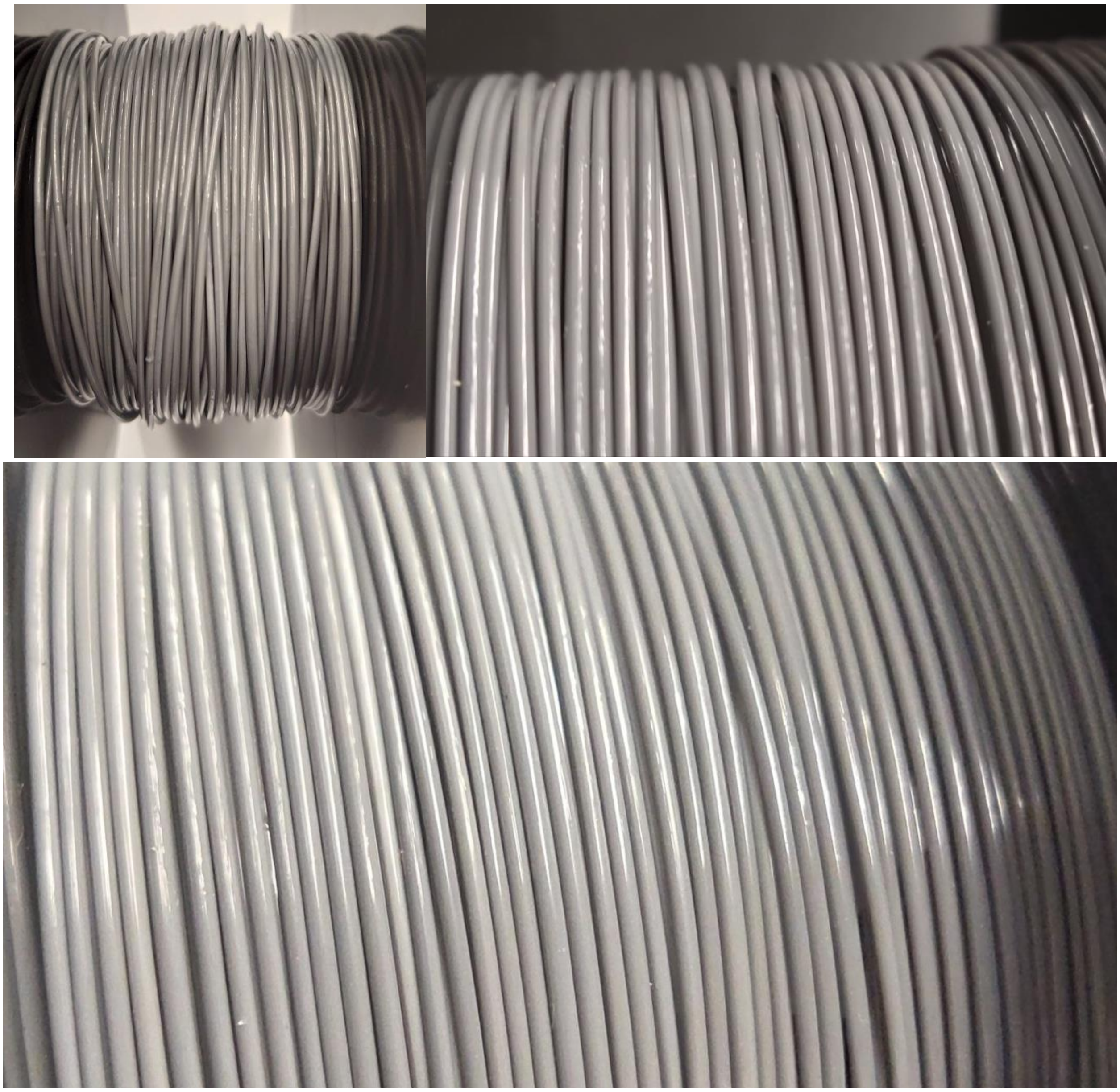

*Figure 4.10: The filament made with the Filastruder and FilaWinder exhibited a uniform and glossy texture.*

### 4.2.3 PET Extrusions

From the unsuccessful extrusion of PET, the group discovered two different extrusion results due to two different types of PET chips. The group found one batch of water bottle chips to result in plastic that was brittle and contained unmelted PET particles within the strands, shown below in Figure 4.11. Another batch of chips from different bottles resulted in smoother strands that were also brittle but did not contain unmelted PET particles in the extrusion. Although both were extruded within a similar environment and the same extrusion temperature, the two varied drastically in appearance.

*Figure 4.11: Unsuccessful PET extrusions show one batch to have a rough texture (top) and another batch to have a smooth texture (bottom).*

### 4.2.4 Filament Discussion

From the measured data points, the extruded and wound PLA filament diameter had an error of ± 0.29 mm while industry standards have an average error of ± 0.02 mm. As such, the recycled filament does not meet industry standards. The team noted that the larger variance may be due to an inconsistent tension on the extruded plastic after it exits the extruder nozzle. While the winder does provide more consistent tension on the extruded filament than the gravity-pulled filament, there is still room for a large amount of variance due to the precision of the spooler. The group observed that when there is a large amount of tension, the filament thins; when there is not enough tension, the filament thickens and warps at the nozzle.

Outside of PLA, the team was unable to successfully extrude PET due to melting issues mentioned in Section 3.3.2. The group considered the possibility of additives playing a large role in making the melting process more complex. It is speculated that due to the PET chips coming from used consumables like water bottles and juice containers, the additives in the material that were meant to improve material performance has altered the melting temperature of the material. While the temperature of the extruder cannot reach a high enough point for the PET to melt, unsuccessful attempts at extruding PET show that it is possible to remelt and extrude PET into filament. The team believes that there is a strong correlation that the low temperature is the primary reason for impeding the extrusion of PET, although this theory requires further investigation.

In terms of investigating why the batches of PET extruded differently, the team theorizes that the cause may be due to the different material composition from each batch of chips. The Dasani water bottles that were shredded and extruded were labeled to be made from up to 30% of plants. The other bottles that were recycled did not mention on their labels that their bottle consisted of anything outside of PET, so the group suspects that the differences in results are due to the plants. However, similar to PLA, the results from extruding PET at below optimal temperatures were brittle and displayed unmelted particles, shown below in Figure 4.12. While not to the same extreme as PET, the brittle PLA from extruding at a lower than optimal temperature may indicate that the Dasani PET requires a higher melting temperature than the other PET to reach a malleable state. Regardless of the reason, the group acknowledges that PET material from Dasani water bottles must be treated differently than other PET bottles without labeled additives to properly extrude.

*Figure 4.12: PLA filament that has been extruded at too low of a temperature exhibits brittleness and a rough surface texture.*

## 4.3 Wound Filament

The FilaWinder was able to successfully wound the extruded filament, shown below in Figure 4.13. As the winder spooled the filament, the filament guide on the winder moved the filament left and right to allow the filament to sit next to each other. While the filament did generally alternate back and forth while it rotated around the spool, it was not as neat or tight as the spooling done by a commercial winder. Since the diameter variation prevented guidance through the given PTFE tube, the filament was guided through an alternative hole on the winder that was big enough the filament and kept tension on it as the spool turned. Although the FilaWinder required some modifications, it served its basic function. The winder does prevent the filament from entangling itself so it is successful in terms of winding filament to store it on a spool and prevent tangling.

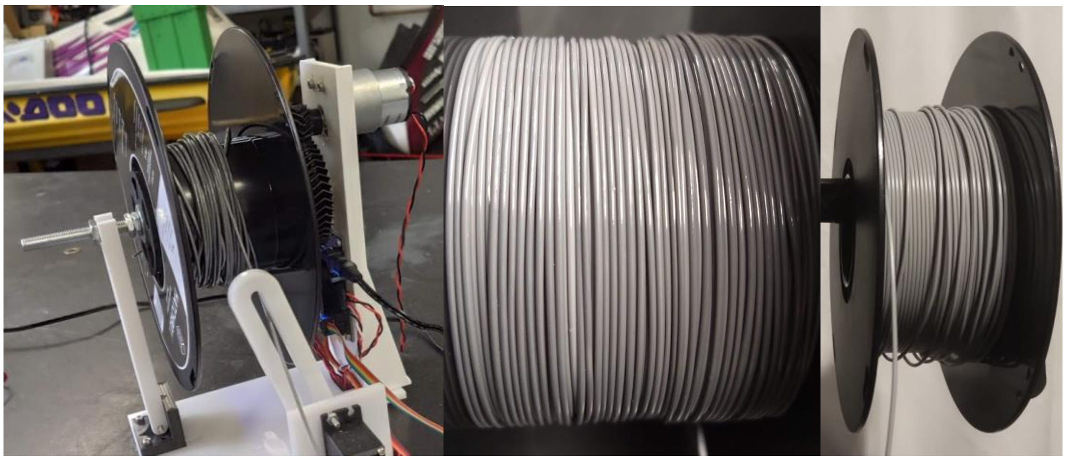

*Figure 4.13: Winder-wound filament (left), hand-wound filament (middle), and commercially-wound filament (right).*

Environmental factors adversely affected the operation of the FilaWinder and the quality of the filament. The sag sensor, which is designed to operate in a controlled environment, is affected by changes in ambient lighting. Even the shadow of a person walking past the mechanism may cause the sensor to report inaccurate values and change the tension on the filament. The sensor has an approximately 2 in detection range, and it was not unusual during testing for the filament to be pulled out of this range when disturbed. In the absence of sensor feedback, the filament could be pulled too much or too little, resulting in an inconsistent diameter and kinks in the filament. Furthermore, the filament cooled quickly after exiting the extruder and had a significant stiffness. The path of the filament between the extruder and winder was not the catenary curve characteristic of a slack rope supported on two ends but was instead a function of the weight and orientation of the filament.

It should be noted that, since the extruder and winder were both mounted horizontally, the angle of the filament to the horizontal was constrained to be zero at both the winder and extruder. This meant that the very malleable filament coming out of the extruder had to bend down due to its own weight, then bend upward at its lowest point, and then bend down again to feed horizontally into the winder. The two inflection points added to the filament by this mounting orientation may have made the system less stable than a similar configuration with both the extruder and winder mounted vertically.

## 4.4 Print Quality

The team tested the filament printability on Prusa i3 Mk3 3D printers with 0.4 mm nozzle diameters. The group first tested the undersized filament from the extruder before the nozzle was expanded. After changing the diameter on the Simplify 3D slicer to be 1.3 mm, the average diameter, the team extruded at the normal PLA extruding temperature of 215°C and print bed temperature of 60°C. Outside the temperature and the filament diameter, all other settings were set at the standard values. The team witnessed the print to be over-extruded and inconsistent with lumps, as shown below in Figure 4.14.

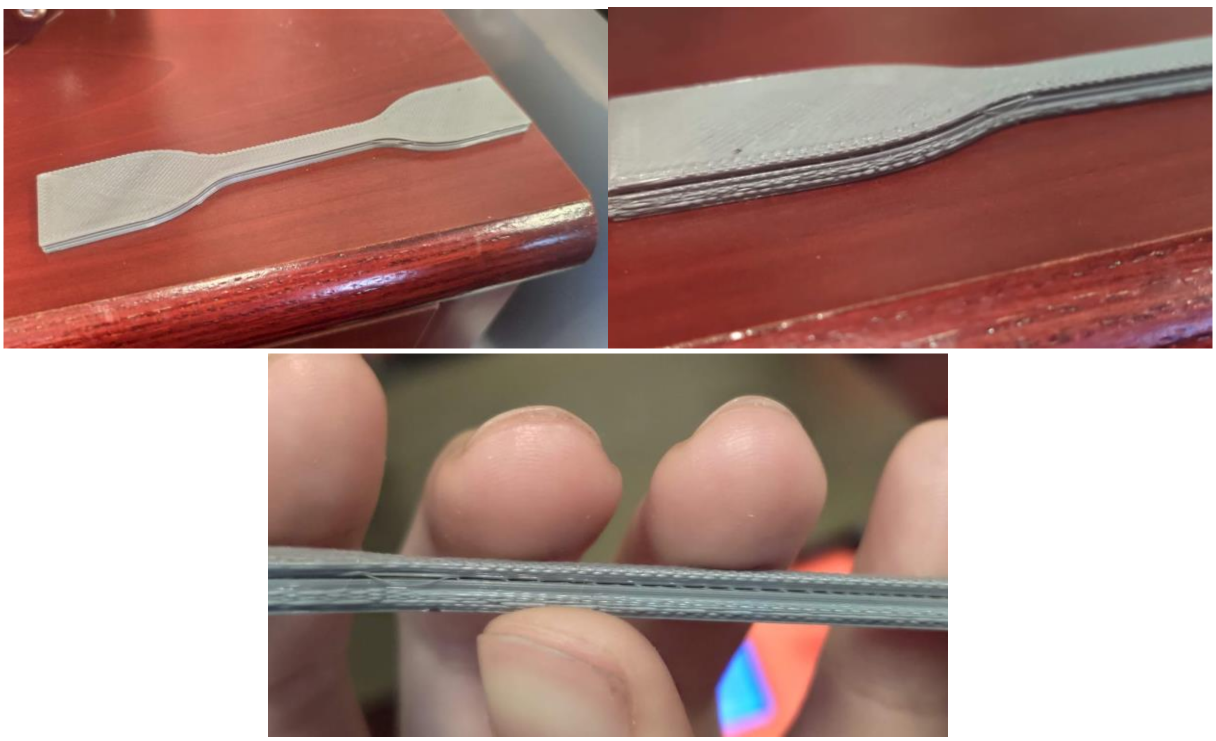

*Figure 4.14: Filament extruded at 215°C exhibited inconsistent extrusion and under-extrusion.*

When experimenting with the temperature, the group found that a printable temperature was approximately 190°C. The 3D printer started printing dogbone specimens for testing and it was able to print a few specimens before it started having issues extruding the filament, shown in Figure 4.15. The large diameter variance resulted in an inconsistent extrusion. After a print finishes the first layer, the print often fails when the nozzle clogs. Following several attempts in reprinting the file while changing the nozzle temperature and nozzle speed, the team determined that the spool of filament was unprintable.


*Figure 4.15: Dogbone test specimens that were printed at 190°C.*

A team member then tried printing the larger diameter filament that was extruded and wound with the FilaWinder. On their slicer, they changed the filament diameter to 1.85 mm, the average diameter of that spool, and left the temperature at 190°C. In an attempt to print, the filament kept clogging the printing head because the gears could not exert enough force on the filament to push it through the nozzle, forcing the stepper motor to skip. The member increased the heating element back to 215°C. While the printer head was able to melt and eject plastic out of the nozzle head at this temperature, the nozzle still clogged often, making the print success rate very low. They further raised the temperature up to 275°C to make sure that the filament, as well as any contaminants that might block the nozzle, would completely melt. The filament was able to extrude at 275°C. However, as it printed over time the filament entering the printer head started to soften and melt onto the extruder gears and prevent the gears from pulling the filament into the heating chamber. They lowered the temperature until the filament stopped melting at the gears at 270°C. The team discovered at that temperature along with a slower nozzle speed of 80% and a nozzle flow rate of 90-100% to reduce under extruding, prints were able to finish with a much higher success rate than previous runs, shown in Figure 4.16. The group was also able to print more figures to test the filament on longer print times and more complex shapes, shown below in Figure 4.17 and 4.18.


*Figure 4.16: Dogbone test specimens and small objects printed at 270°C.*

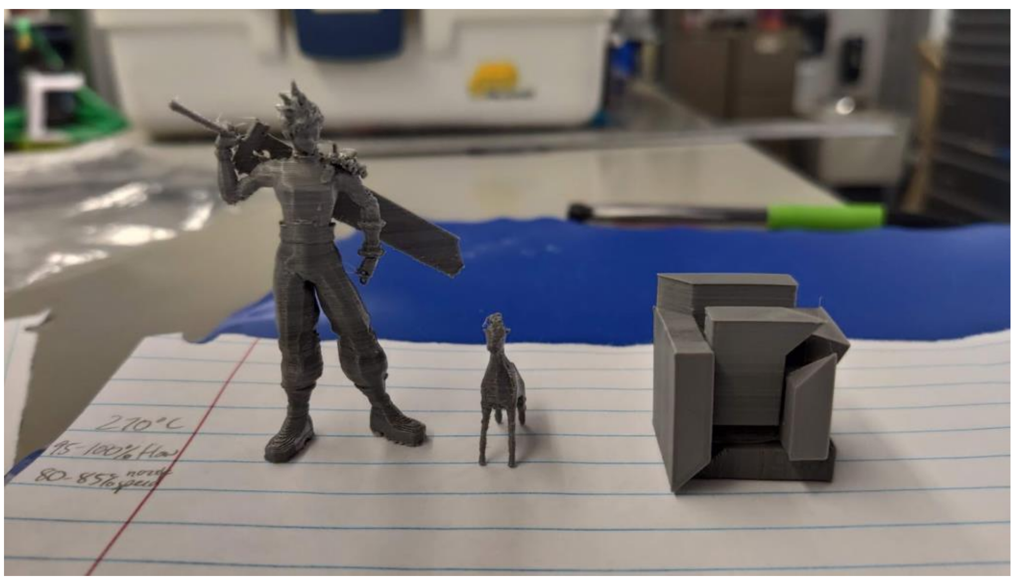


*Figure 4.17: A 3D-printed Cloud Strife figurine, goat, and cube puzzle from recycled filament.*

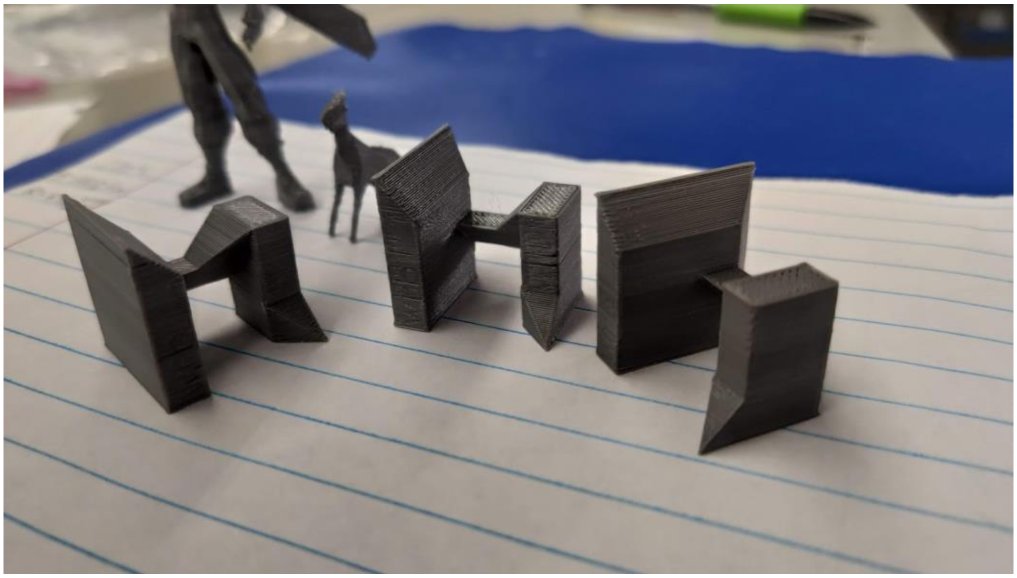

*Figure 4.18: 3D printed puzzle pieces.*

The team inspected the surface and layers of the printed parts and found imperfections that are not often seen with high-quality filament prints, shown below in Figure 4.19. When looking at the layers, there was evidence of under-extrusion from the variance in filament diameter when the extruder was pushing out filament through the nozzle, shown in Figure 4.20.

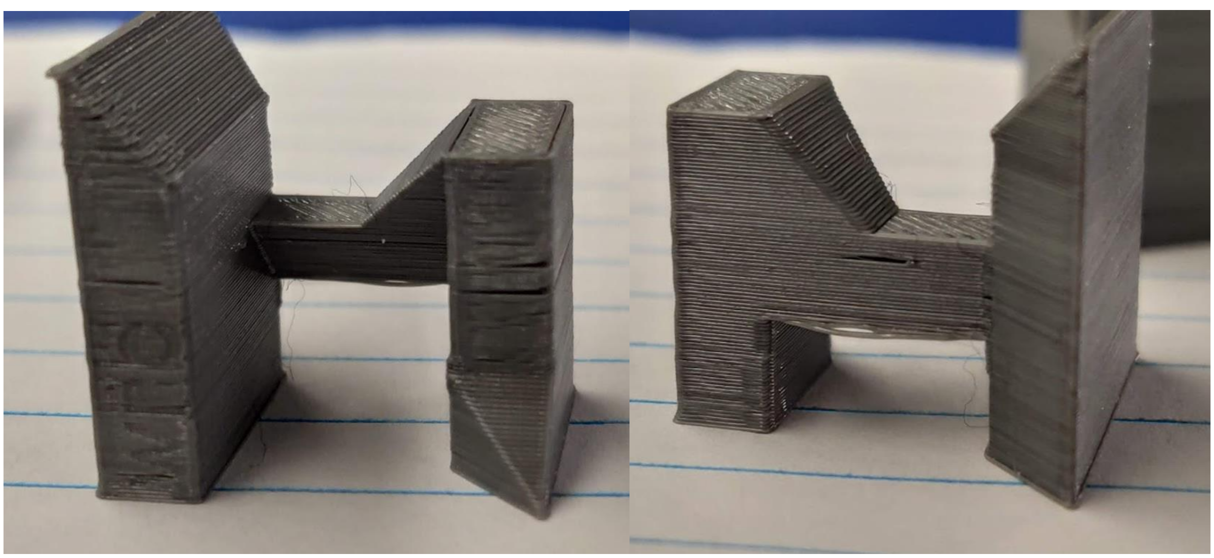

*Figure 4.19: Cube puzzle pieces printed at 270°C exhibited a rough surface texture.*

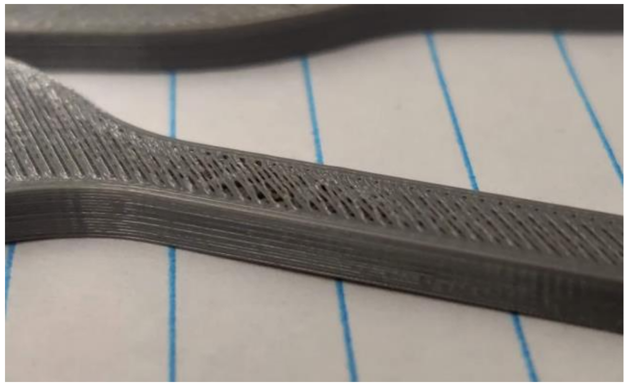

*Figure 4.20: A dogbone specimen printed at 270°C exhibited under-extrusion.*

### 4.4.1 Print Quality Discussion

The print settings and quality of the prints are subject to the set values mentioned above specifically for the filament the group made with the extrusion parameters specified in Section 4.4. If the filament had a smaller variance that was closer to commercial tolerances, the team speculates that the success rate and quality might have been higher. When testing, the group originally theorized that the standard melting temperature of 215°C would be high enough to melt and extrude the filament. Although when it clogged at that temperature, the nozzle temperature had to be raised to 275°C for it to continuously print without jamming. There may be contaminants within the filament that hindered the extrusion, whether it be due to size or being unable to melt at the nozzle. A team member reported that 215°C would be an appropriate temperature to melt the filament if there were no contaminants since it was able to load into the extruder head without any issues. Contaminants in the filament could have been from remnant plastic from a previous extrusion or shaved-off metal particles from the extruder barrel due to cantilevering. Therefore, the printer was set to 275°C to melt any possible contaminants that did not melt at 215°C. Other than contaminants, it is possible that the material properties changed since the plastic has already been through a minimum of two heat cycles.

The printed parts looked to be of acceptable quality, though flaws can be spotted with closer examination. From inconsistencies in extrusion such as under-extrusion, a few layers of a print were much thinner than its neighboring layers which resulted in gaps that may cause future delamination or fractures if subject to stress. The print layers did not exhibit a smooth surface on the sides due to the inconsistent extrusion so prints from the made filament may not be suitable for printing outside of prototype pieces.

## 4.5 Mechanical Testing

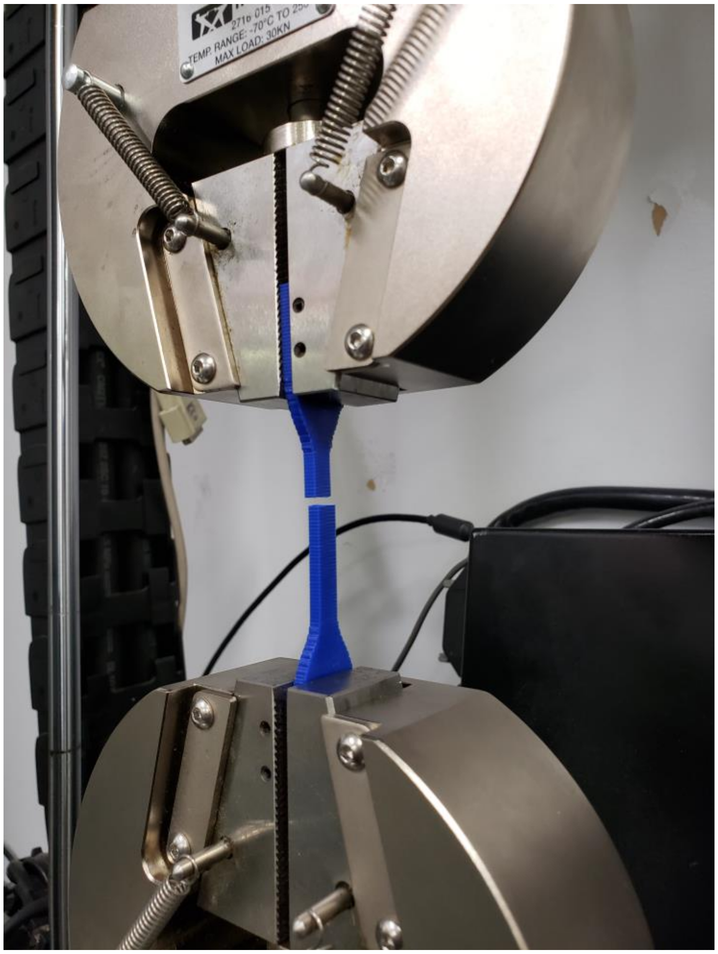

*Figure 4.21: Instron tensile test with a commercial PLA sample.*

The transverse test specimens had consistent results except for one, as shown in Figure 4.22. The outlier may have been due to the recalibration not being completed before the test began. When the displacement was zeroed, the initial displacement appeared as negative due to calibration offsets. The results calculated from the stress-strain graph, shown in Table 4-1, include three properties: ultimate tensile stress (UTS), 0.2% yield stress, and Young's modulus.

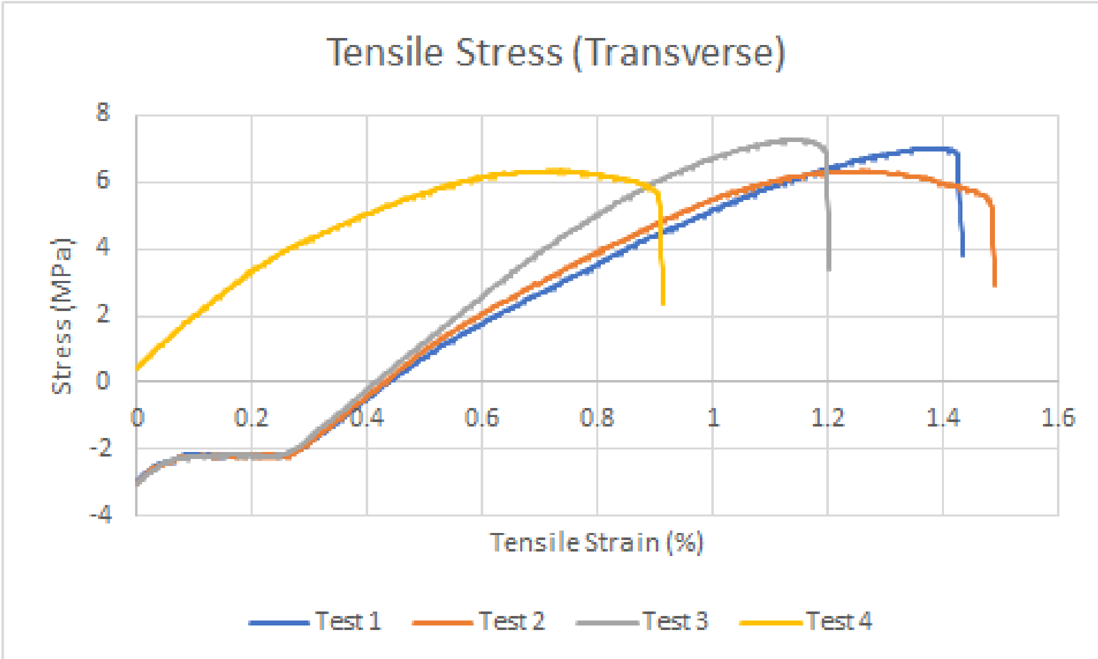


*Figure 4.22: Tensile test of transverse dogbone specimens (without vertical axis offset to 0).*

*Table 4-1: Transverse test results with an offset added for the true values of mechanical properties.*

| Parameter | Test 1 | Test 2 | Test 3 | Test 4 |
|---|---|---|---|---|
| Ultimate Tensile Stress | 10.0108 MPa | 9.3685 MPa | 10.3259 MPa | 6.3471 MPa |
| 0.2% Yield Stress | 0.8486 MPa | 0.8526 MPa | 0.8496 MPa | 3.3363 MPa |
| Young’s Modulus | 7.6966 MPa | 7.8417 MPa | 10.0487 MPa | 9.5240 MPa |

The properties listed on the table are the actual values after considering the vertical offsets. For instance, the ultimate tensile stress of Test 1 appears as approximately 7 MPa on the graph; with an offset, the actual value is roughly 10 MPa.

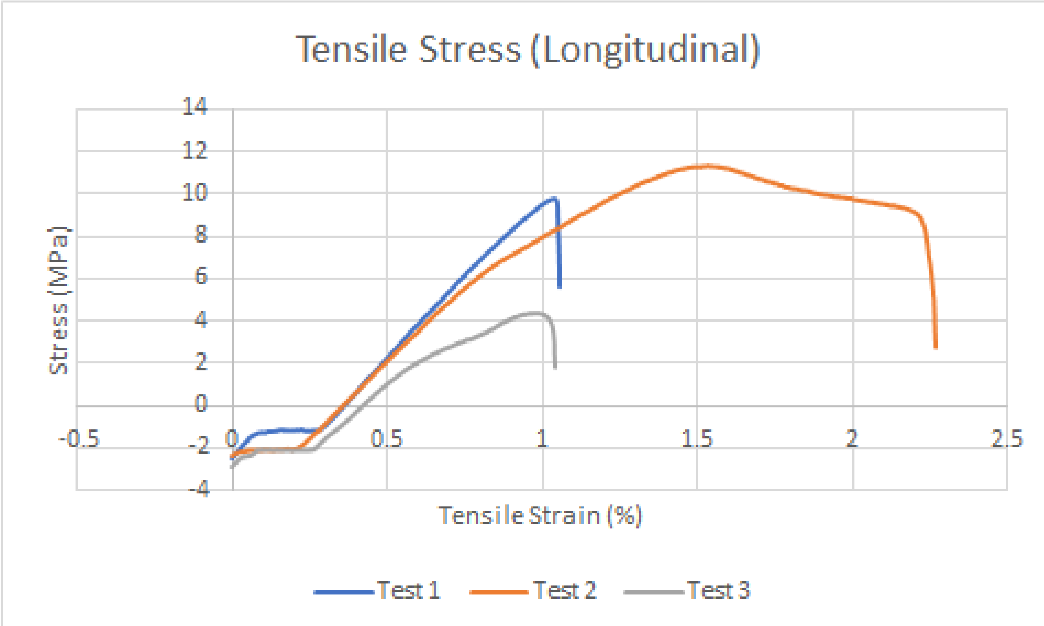


*Figure 4.23: Tensile test of commercial longitudinal dogbone specimens (without vertical axis offset to 0).*

*Table 4-2: Longitudinal test results with an offset added for the true values of mechanical properties.*

| Parameter | Sample 1 | Sample 2 | Sample 3 |
|---|---|---|---|
| Ultimate Tensile Stress | 12.2585 MPa | 13.7331 MPa | 7.2555 MPa |
| 0.2% Yield Stress | 1.3068 MPa | 0.4096 MPa | 0.7739 MPa |
| Young’s Modulus | 14.0290 MPa | 8.9397 MPa | 7.1283 MPa |

Tensile test specimens that were oriented longitudinally had varying results, seen in Figure 4.23 and Table 4-2. There were discontinuities within most of the prints from 3D printing, as shown in Figure 4.24. When the specimens broke during testing, the fracture location was where the discontinuity was originally present. One of the tests had significantly more data points present due to the printed specimen not having any dislocations present in the test length. Similar to the results of the transverse samples, the initial displacement still appeared as negative even though the displacement was recalibrated before the start of each test. In comparison to the transverse specimen results, the longitudinal tests had a higher strength. The anisotropic behavior is reasonable because the inter-layer adhesion strength was measured from the transverse specimens while the material strength was measured from the longitudinal specimens.

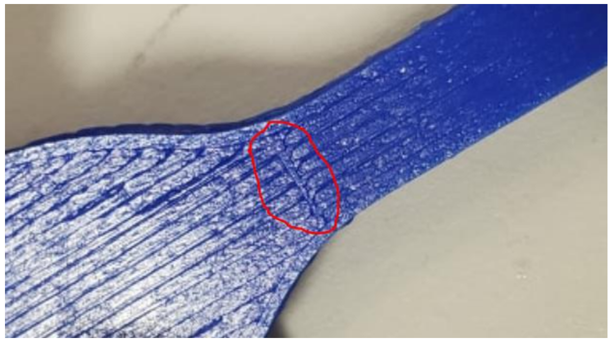

*Figure 4.24: Inconsistent pattern on the longitudinal prints due to the print layer starting and ending within the test length.*

Overall, the mechanical properties of the Hatchbox samples were much lower than the expected values for commercial PLA. Typically, PLA plastic has a 0.2% yield strength at approximately 59 MPa with the ultimate tensile stress and Young's modulus estimated to respectively be at 73 MPa and 1280 MPa (Farah, 2016). The results may have been affected due to the dislocations that were present within each of the samples. The orientation of the prints may have also created potential dislocations that would have caused a decrease in strength. To validate the sources of error, the team planned to measure the mechanical properties of 3D printed specimens with a 45-degree orientation, which is the typical orientation for 3D prints. Additionally, to test the tensile properties of the team's extruded filament, the team decided to print the recycled specimens with a 45-degree orientation due to 3D prints normally being printed in this orientation.

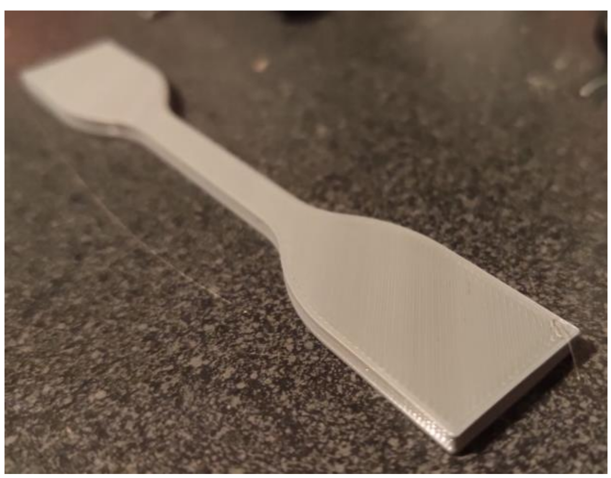

*Figure 4.25: 45-degree oriented dogbone specimen made from recycled filament.*

The previous test results showed the variability of commercial filaments. The team was in the process of testing the recycled filaments for direct comparison when the mandatory campus evacuation occurred due to the COVID-19 pandemic. Consequently, comparison tests were not completed.

# 5 Conclusion and Recommendations

## 5.1 Shredding Recommendations

From the results that were discussed above, the team believes that small-scale plastic resizing is feasible via a jointer. The finer chips, typically under 5 mm in all dimensions, that were obtained from the jointer and micro-cut paper shredder showed promising results in the extruding process.

As the team was having problems with a portion of the chips flying out of the gap between the bottom of the jointer and the hopper of the micro paper shredder, it is recommended to add a completely enclosed shroud above the paper shredder hopper to minimize the gap. This modification will allow the chips to fall directly into the hopper of the micro-cut paper shredder, reducing the volume loss from stray chips flying away. Clearance between the 80/20 framework and the side walls should also be properly adjusted to further prevent chips from moving through the gaps.

In its current state, the jointer is manually operated. The team believes implementing an automated motor-and-belt system would be beneficial to the jointer housing to reduce the amount of manual labor. Additionally, the jointer emitted extremely loud noise during operation. The wood and acrylic side walls provided limited noise reduction. Therefore, the team recommends adding noise-dampening insulation in the housing design. Lastly, instead of using straight-blades that were featured in the jointer, helical cutterheads should be considered for future designs. The segmented blade configuration commonly seen on helical cutterhead could provide finer and more uniform chip formation and reduce the level of sound produced by the shredding process.

## 5.2 Extruding Recommendations

While the Filastruder is a convenient and adequate way to produce recycled plastic filament, there are many ways in which the core design behind it may be modified to enhance its effectiveness. The electrical and mechanical changes that can be made to the Filastruder are discussed below.

The extruder is powered by a 60 W, 12 V power supply, which branches into two circuits in the manufacturer's recommended wiring layout: the heating system, and the auger screw. The screw branch includes the gear motor to drive the auger screw and two 12 V DC muffin fans wired in parallel. One of these fans cools the motor compartment and the other is intended to cool the filament as it exits the nozzle. When connected, both fans run directly from the power supply's 12 V input to ground. This means that both fans are either fully on or off, and cannot be variably adjusted. It also means that the fans cannot be turned on unless the entire screw branch is connected to power. An alternative configuration would be to remove one or both fans from the screw branch so that they may be used without the auger motor running and add a potentiometer (or similar means of controlling motor speed) to the filament-cooling fan to make it adjustable. A higher-power heating element could also be used to allow for greater throughput of the extruder.

The Filastruder's extruder barrel is made from a ½-in steel pipe with the interior weld bead ground off and a section milled out to allow space for a hopper. The pipe is threaded into a connector for the nozzle on one side and into a bolted flange on the other. The tapered pipe thread between the flange and the pipe allows the barrel to yield under excessive load without any actual mechanical failure. This setup is a cost-effective and fairly functional way to extrude plastic, but it could be improved with some additional time and money. Instead of being made of rolled sheet metal, the barrel could be machined in two parts as a clamshell assembly, the interior of which could be finished and roughened to an actual standard. This would also require reworking the mounting flange for the barrel.

The extruder screw on the Filastruder is nothing more than a wood drill bit with the end filed off. The land of this drill bit is fairly large and may contribute through friction to the motor overloading that was observed in testing. Similarly sized, purpose-built extruder screws exist and might be less prone to jamming the extruder. This would require additional resources to test and implement. The current FilaWinder design also has the screw supported by the inside of the extruder barrel, causing the two to rub together and produce metallic contaminants. The assembly could be oriented vertically to minimize gravitational effects and lessen the scraping between the screw and the pipe. The screw could also be located more precisely with an additional bearing to support the otherwise cantilevered portion of the screw.

The Filastruder has no integrated hopper, and the team had to 3D print several different parts to fill this role. Each one of the printed hoppers was eventually warped by pressure from oversized chips being shorn off at the mouth of the barrel's input cutout. The team did make the hopper modular so that part failure was relegated to a single small, replaceable part of the hopper assembly, but the problem could be avoided altogether if the hopper were made from stronger materials. Adding a welded steel hopper to the extruder would make the assembly more robust.

## 5.3 Winding Recommendations

The FilaWinder has demonstrated itself to be a functional—albeit temperamental — method of winding filament from the Filastruder. There are some aspects of the design that could be improved. The filament sag sensor is very sensitive to changes in ambient lighting conditions and should be kept away from light sources that have the potential to change over time. An enclosure may also be made for the sensor to minimize interference. It should have a ceiling to physically limit how high the filament can travel above the photoresistors. The winder setup may produce more consistent results if both the extruder and winder are oriented vertically, to simplify the path taken by the filament between the two. The current stock design of the FilaWinder is controlled by an Arduino Nano, which makes use of a line-tracking Arduino library and a PID loop to maintain the filament's position within the sensor by varying the speed of the spooling motor. The sag sensor could conceivably be directly replaced by the filament diameter sensor discussed in Section 3.4.1, with variables specific to the photoresistor array being replaced by the error between the measured filament diameter and reference value. This change can be made without changing the rest of the FilaWinder hardware.

## 5.4 Conclusion

To address the increasing environmental concerns surrounding sustainability for plastics, the team has completed a proof-of-concept recycling system and demonstrated the feasibility of implementing a small-scale, low-budget solution to recycle PLA waste into functional filament. While the team was not able to quantitatively test the quality of the recycled filament, the results were comparable to commercial filament to a certain extent. The team has identified sections of processes in the system that could be further developed for better results and hope that the project results can support further research on improving sustainability for 3D printing technology.

# Resources


3D-Fuel. (2019). Filament Quality. Retrieved from https://www.3dfuel.com/pages/filament-quality

3Devo. (2019, February 13). Should You Buy A Filament Extruder? - 3devo blog. Retrieved from https://3devo.com/blog/should-you-buy-a-filament-extruder/

3DSupplyGuys. (2019). Cheap 3D Filament: Is it Worth the Cost? Retrieved from https://3dsupplyguys.com/blogs/3d-printing-education/cheap-3d-filament

All3DP. (2019, September 4). 2019 PLA Filament Guide – All You Need to Know. Retrieved from https://all3dp.com/1/pla-filament-3d-printing/

Anand, M. (2019, September 13). Personal interview.

Anderson, I. (2017, June 1). Mechanical Properties of Specimens 3D Printed with Virgin and Recycled Polylactic Acid. Retrieved from https://www.liebertpub.com/doi/10.1089/3dp.2016.0054

ASTM International. (2004). Standard Test Method for Compressive Properties of Rigid Cellular Plastics. Retrieved February 15, 2020, from https://compass.astm.org/EDIT/html_annot.cgi?D1621+16

ASTM International. (2004). Standard Test Method for Tensile Properties of Plastics. Retrieved February 15, 2020, from https://www.astm.org/Standards/D638.htm

Bonifazi, G., & Serranti, S. (2019, January 25). Techniques for separation of plastic wastes. Retrieved from https://www.sciencedirect.com/science/article/pii/B9780081026762000025.

Bouthillier, J. L. (2016, February 10). The Importance of High Quality 3D Printer Filament. Retrieved from http://bootsindustries.com/the-importance-of-high-quality-3d-printer-filament/

Cao, M. (2017, January 31). Recycled Plastic Vs Virgin Resin – More Than Just a Coin Toss. Retrieved from https://ic3dprinters.com/recycled-plastic-vs-virgin-resin-just-coin-toss/

Carlson, C., & Capitaine, S. L. (2019). The Role of Drying in Agglomeration. Retrieved from https://feeco.com/role-drying-agglomeration/

Cho, R. (2017, December 13). The Truth About Bioplastics. Retrieved from https://blogs.ei.columbia.edu/2017/12/13/the-truth-about-bioplastics/

CNC Kitchen. (2018, November 10). *Recycle your failed 3D prints! Make new filament at home*. [Video file]. Retrieved from https://www.youtube.com/watch?v=vqWwUx8l_Io

Conz. (2014, May 2). Extruding your own filament. Retrieved from https://community.ultimaker.com/topic/5090-extruding-your-own-filament/

Drumright, R. E., Gruber, P. R., & Henton, D. E. (2000). Polylactic acid technology. *Advanced materials*, *12*(23), 1841-1846.

Dubashi, J., Grau, B., & McKernan, A. (2015, June 8). AkaBot 2.0: PET 3D Printing Filament From Waste Plastic. Retrieved from https://scholarcommons.scu.edu/cgi/viewcontent.cgi?article=1043&context=mech_senior.

Dufour, F. (2018, December 20). A whopping 91% of plastic isn't recycled. Retrieved from https://www.nationalgeographic.com/news/2017/07/plastic-produced-recycling-waste-ocean-trash-debris-environment/

Dvorak, R., Hopewell, J., & Kosior, E. (2009). Plastics recycling: challenges and opportunities. Plastics recycling: challenges and opportunities. The Royal Society Publishing. Retrieved from https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2873020/

Ecology Center. (2001). Adverse Health Effects of Plastics. Retrieved from https://ecologycenter.org/factsheets/adverse-health-effects-of-plastics/

EPA. (2019, May 7). Plastics: Material-Specific Data. Retrieved from https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/plastics-material-specific-data

Farah, S., Anderson, D. G., & Langer, R. (2016). Physical and mechanical properties of PLA, and their functions in widespread applications — A comprehensive review. *Advanced Drug Delivery Reviews*, *107*, 367–392. doi: 10.1016/j.addr.2016.06.012

Fila-Cycle. (2015). About. Retrieved from http://www.fila-cycle.com/

Filamentive. (2019). Making High Quality Recycled 3D Printer Filament. Retrieved from https://www.filamentive.com/making-high-quality-recycled-3d-printer-filament/

Filastruder. (2019). Filastruder Kit. Retrieved from https://www.filastruder.com/collections/filastruders-accessories/products/filastruder-kit

Filastruder. (2019). Filawinder. Retrieved from https://www.filastruder.com/products/filawinder?_pos=1&_sid=5e319852a&_ss=r.

Flynt, J. (2017, September 10). Cost of 3D Printing Material: Filament Cost of PLA, ABS, and more. Retrieved from https://3dinsider.com/3d-printing-filament-cost/

FormLabs. (2019). How to Choose the Right 3D Printing Material: Understanding Material Properties of Plastics. Retrieved from https://archive-media.formlabs.com/upload/how-to-choose-the-right-3D-printing-material.pdf

Gendell, A. (2017, July 20). 101: Resin Identification Codes. Retrieved from https://sustainablepackaging.org/101-resin-identification-codes/.

Gerlat, A. (2018). The promise of chemical recycling. Retrieved from https://www.recyclingtoday.com/article/the-promise-of-plastics-chemical-recycling/

Guern, C. L. (2018, March). When The Mermaids Cry: The Great Plastic Tide. Retrieved from http://plastic-pollution.org/

Hallo, B. (2015, July). Which shredding and extruding machines are available: Part 3. Retrieved from https://www.3dhubs.com/talk/t/which-shredding-and-extruding-machines-are-available-part-3/2008

Henry, K. (2015, August 3). Sensor-Based Sorting Revolutionizes Plastics Recycling. Retrieved from https://www.environmentalleader.com/2015/07/sensor-based-sorting-revolutionizes-plastics-recycling/.

Herbold. (2019). Washing lines for washing, separating, drying. Retrieved from https://www.herbold.com/en/machines/washing-separating-drying-2/

Hurd, D. J. (1997). Best Practices and Industry Standards in PET Plastic Recycling" for Washington State Department of Community. *Trade and Economic Development's Clean Washington Center,* 1-55.

Iowa State University Computation and Construction Lab. (2020). 3D Print Recycling. Retrieved from http://ccl.design.iastate.edu/3d-print-recycling/

Jamison, J. (2010, April 6). Handling, drying, and reclaim considerations for PLA. Retrieved from https://www.plasticstoday.com/content/handling-drying-and-reclaim-considerations-pla/69656597014014

Johnson, P. H. (2011). *Optimal Process Design for Recycled Pet Blends in Injection Molding*. Retrieved from https://pdfs.semanticscholar.org/63da/0976755b754931c93c978bc739bebd2e981e.pdf

Jones, M. (2019, December 19). PETG/PLA Recycling: How to Recycle 3D Printer Waste. Retrieved from https://all3dp.com/2/3d-printer-recycled-plastic-tips-for-your-waste-plastic/

joshmt2012. (2017, September 26). Low Cost Plastic Shredder. Retrieved from https://www.instructables.com/id/Low-Cost-Plastic-Shredder/

Kerns, J. (2018, June 28). Recycle at Home with 3D Printing. Retrieved from https://www.machinedesign.com/3d-printing/recycle-home-3d-printing

Laermann, M. (2019). Chemical recycling of plastic: Waste no more? Retrieved from https://sustainablebrands.com/read/chemistry-materials-packaging/chemical-recycling-of-plastic-waste-no-more

Lanzotti, A., Martorelli, M., Maietta, S., Gerbino, S., Penta, F., & Gloria, A. (2018, July 18). A comparison between mechanical properties of specimens 3D printed with virgin and recycled PLA. Retrieved from https://www.sciencedirect.com/science/article/pii/S2212827119301441

Lashof, D. A., & Ahuja, D. R. (1990). Relative contributions of greenhouse gas emissions to global warming. Nature, 344(6266), 529-531.

Lebreton, L., Slat, B., Ferrari, F., Sainte-Rose, B., Aitken, J., Marthouse, R., … Reisser, J. (2018, March 22). Evidence that the Great Pacific Garbage Patch is rapidly accumulating plastic. Retrieved from https://www.nature.com/articles/s41598-018-22939-w.

Lulzbot. (2014, March 17). Measuring 3D Printed Material Strength. Retrieved from https://www.lulzbot.com/learn/in-the-news/measuring-3d-printed-material-strength

Madaan, S. (2016, December 23). Fatal Effects of Plastic Pollution. Retrieved from https://www.eartheclipse.com/pollution/fatal-effects-of-plastic-pollution.html

Make:. (2015, February 11). *How It Is Made: 3D Printing Filament.* [Video file]. Retrieved from https://www.youtube.com/watch?v=OEkksADFjP8

McCauley, K. (2017, October 10). 8 Things You Need To Know About PLA Plastic Packaging. Retrieved from http://lawprintpack.co.uk/packaging/8-things-you-need-to-know-about-pla-plastic/

MoKell 8pcs CY-16B 5/8-inch Bearing Steel Roller Ball Flange Conveyor Transfer Unit. (2011). Retrieved from https://www.amazon.com/gp/product/B07ZHZXVJJ/ref=ppx_yo_dt_b_asin_title_o00_s00?ie=UTF8&psc=1

Neflatek. (2019, September 16). About Us. Retrieved from https://nefilatek.com/a-propos/

Obama, B. H. (2013, February). 2013 State of the Union Address. 2013 State of the Union Address. Washington, D.C. Retrieved from https://obamawhitehouse.archives.gov/the-press-office/2013/02/12/remarks-president-state-union-address

Obudho, B. (2019, February 1). The Best Filament Extruders to Build or Buy. Retrieved from https://all3dp.com/2/6-best-filament-extruders-to-build-or-buy/

PET Resin Association. (2015). About PET. Retrieved from http://www.petresin.org/aboutpet.asp

Piemonte, V. (2011). Bioplastic wastes: the best final disposition for energy saving. *Journal of Polymers and the Environment*, *19*(4), 988-994.

Plasgran. (2015). How is plastic recycled? - plasgran plastic recycling specialists. Retrieved from https://plasgranltd.co.uk/how-is-plastic-recycled/

Plastic extruder cut in half and labeled. (2006). Retrieved from https://commons.wikimedia.org/wiki/File:Extruder_section.jpg

Plastics Industry Association. (2018). Recycling 101: Advanced recycling. Retrieved from https://www.ThisIsPlastics.com/environment/recycling-101-advanced-recycling/

Popescu, O., & Slavikova, S. (2018). Step by step process of recycling plastic | greentumble. Retrieved from https://greentumble.com/how-is-plastic-recycled-step-by-step/

Precious Plastic. (2016). Build the shredder. Retrieved from https://preciousplastic.com/en/videos/build/shredder.html.

PRM Environmental and Recycling Research and Development Institute. (2013). Sink / Float Separation Tank - Plastic Recycling Machine: High-Quality Machinery For Plastic Recycling. Retrieved from https://www.plasticrecyclingmachine.net/sink-float-separation-tank/.

PRUSA. (2019). The Story Behind Prusament: Prusament. Retrieved from https://prusament.com/story-behind-prusament/.

ReDeTec. (2019). ProtoCycler. Retrieved from https://redetec.com/pages/protocycler.

Refil. (n.d.). About. Retrieved from https://www.re-filament.com/about

Rogers, T. (2015, October 7). Everything You Need To Know About Polylactic Acid (PLA). Retrieved from https://www.creativemechanisms.com/blog/learn-about-polylactic-acid-pla-prototypes

Royte, E. (2006). Corn plastic to the rescue. *Smithsonian Magazine*, *37*(5), 84-88.

Sedaghat, L. (2018, April 4). 7 Things You Didn't Know About Plastic (and Recycling). Retrieved from https://blog.nationalgeographic.org/2018/04/04/7-things-you-didnt-know-about-plastic-and-recycling/

Precious Plastic Community Platform. (2016). Retrieved from https://community.preciousplastic.com/academy/build/shredderpro

Statista. (2018, May). Uses for 3D printing 2015-2018. Retrieved from https://www.statista.com/statistics/560271/worldwide-survey-3d-printing-uses/

Subramanian, P. M. (2000). Plastics recycling and waste management in the US. Resources, Conservation and Recycling, 28(3-4), 253-263.

Surfers Against Sewage. (2019). Plastic Pollution - Facts and Figures . Retrieved from https://www.sas.org.uk/our-work/plastic-pollution/plastic-pollution-facts-figures/

TechforTrade, ReFab Dar, World Bank Group, Enviu, STICLab, & Buni. (2016, March). Feasibility Study: Production of Recycled 3D Print Filament. Feasibility Study: Production of Recycled 3D Print Filament (pp. 14–15).

The Plastic Industry Trade Association. (2015). SPI Resin Identification Code - Guide to Correct Use. Retrieved from https://web.archive.org/web/20160126213345/http://www.plasticsindustry.org/AboutPlastics/content.cfm?ItemNumber=823&navItemNumber=1125.

TranPak. (2010). Plastic Pallet Materials: Choose Virgin or Recycled Resins. Retrieved from https://www.tranpak.com/plastic-pallets/important/part-3/

Vargas, M. (2009, October 19). Polyethylene terephthalate (pet, #1). CalRecycle. Retrieved from http://www.calrecycle.ca.gov/Plastics/markets/PETEProfile.html

Vista Industrial Products, Inc. (2018, April 10). RoHS vs. REACH Compliance Explained. Retrieved from http://www.vista-industrial.com/blog/rohs-vs-reach-compliance-explained/

# Appendices

## Appendix A: Functional and Design Requirements

### Functional Requirements

1. Shredder
    a. Output chips shall be no more than 5 mm in any dimension
    b. Output chips shall be solid and unmelted
    c. Input plastic size is to be constrained to an 8 in x 8 in x 6 in volume
    d. The system shall be capable of shredding PLA and PET plastic at room temperature
    e. Cannot jam or glaze plastic parts
    f. Functions independently from other processes
2. Dehydrator
    a. Chips must have a moisture level below 8%
    b. Functions independently from other processes
3. Extruder
    a. Filament outputs at a consistent diameter and roundness within ± 0.05 mm
    b. Input and output plastic shall be free of contaminants and air/moisture bubbles
    c. Input plastic must be no larger than 5 mm in any dimension
4. Spooling
    a. The spooler must wind filament onto a filament spool without entanglement
    b. Spools at a consistent diameter
    c. The extruder and spooler shall work synchronously

### Design Requirement

1. Shredder
    a. Cutting blades shall rotate at a constant speed between 3,000 and 10,000 RPM
    b. Cutting blade shall have sufficient torque to avoid binding/jamming
    c. Shredder frame shall be securely mounted on the jointer table with no play
    d. The system shall include an main power switch for the entire mechanism
    e. Interior sections of the shredder shall be easily accessible for maintenance
    f. The shredder shall include safety guards and mechanisms to avoid safety hazards
    g. All cutting surfaces shall be fully enclosed
    h. Hopper size can fit normal water bottles and a large volumetric portion of the Foisie Makerspace printer beds
    i. Plunger pushes plastic towards the cutting blades
    j. Plastics will not directly fall onto the cutting blades
    k. The chips will fall below the cutting blades after being cut

l. The amp drawn shall be less than 20 A on a 120 V outlet
m. The blades will shave the part to form 1-2 mm chips
n. The plunger has to have a locking mechanism when fully retracted
o. Left pusher has to be synchronized with a plunger when moving back and forth to shred the plastic
p. Noise pollution must be within a tolerable hearing level without ear protection

2. Dehydrator
    a. Have adjustable thermostat for dehydrating
    b. Have a mesh bag for holding plastic chips within the dehydrator
    c. Average dehydrator size of 13 in x 13 in x 11 in
3. Extruder
    a. Plastic is heated to a range between glass-transition to melting temperature in the auger
    b. The extruder is run at constant 12 V input, between 1.5 A and 1.7 A.
    c. The extruder extrudes at approximately 0.25 kg/hr
    d. Other than the nozzle, all other heated components must be insulated or guarded to prevent burning
    e. Dangerous fumes or substances that are exposed to the air from extrusion as a safety hazard must be kept within an enclosure or a well-ventilated area
    f. Open fiberglass insulation must be covered
    g. Extruder must be appropriately positioned with respect to the spooler
    h. The extruder requires minimal human intervention when feeding chips in
4. Spooling
    a. Need to maintain constant tension from the extruder to achieve a 1.75 mm within ± 0.05 mm with closed-loop feedback
    b. Spooling mechanism size is based off the standard spool size that available at WPI Makerspace and accommodates for multiple spool size
    c. Filament guide is adjusted either electronically or using a worm screw

# Appendix B: Motorized Archimedes Screw Hopper

*Figure B.1: Motor attached to Archimedes screw for the extruder hopper.*

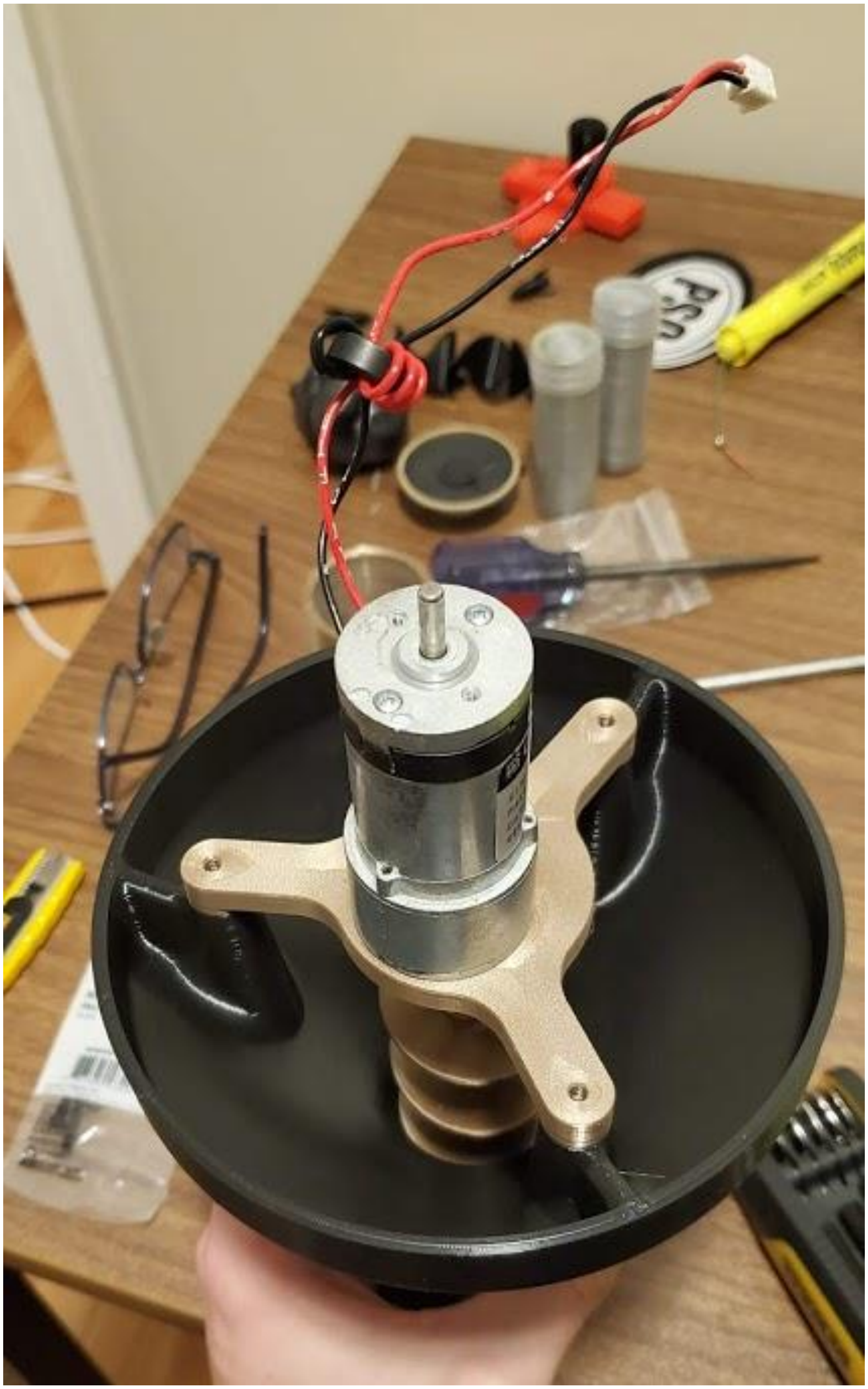

*Figure B.2: Screw and motor assembly onto the extruder hopper.*

# Appendix C: Extruded Filament Documentation

Below is a list and description of the filament the team has extruded.

1. Filament 1
    a. Mass: 5 grams
    b. Color: White
    c. Diameter: 1.09-1.16 mm (Generally consistent)
    d. Printability: Not printable since the diameter is too small. If diameter was not an issue, it should be printable
    e. Visual: Small metal contaminants from the extruder but relatively clean. No excessive warps or bends.
    f. Extrusion Temperature: 170°C
    g. Extrusion Observations and Notes: The filament is made from cut up Hatchbox white PLA filament after all the Hatchbox spool PLA chips ran out in the hopper. The lack of pressure from the screw to push it out caused a smaller diameter. It is not very brittle but the thin diameter makes it easy to snap.

*Figure C.1: Undersized white filament.*

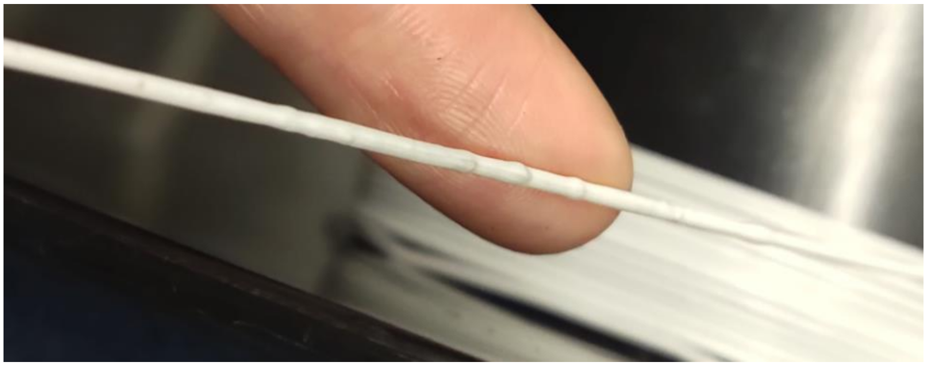

*Figure C.2: The filament has a few contaminants visible.*

2. Filament 2
    a. Mass: 7 grams
    b. Color: Black and greyish mix with small sections of white at the end
    c. Diameter: 1.46-1.5 mm (Somewhat consistent diameter)
    d. Printability: Would not recommend printing since the filament is not smooth with unmelted chunks in some sections.
    e. Visual: Light contaminants with a few warps and bends. There are a lot of sections that have unmelted PLA extruded through.
    f. Extrusion Temperature: ~160-165°C then to 170°C near the whitish ends
    g. Extrusion Observations and Notes: Extruded with the black and white shredded chips from failed PLA parts on from the jointer and the paper shredder. Used unfiltered chips that were dropped into the hopper a small pinch at a time. Filament is somewhat brittle.

*Figure C.3: Filament diameter is consistent excluding the areas with unmelted PLA sections.*

3. Filament 3
    a. Mass: 11 grams
    b. Color: White and black gradient throughout the spool.  Color starts with a darker gray and ending with white
    c. Diameter: 1.36-1.65 mm (Not very consistent. Some areas are visibly thicker)
    d. Printability: The spool itself is rather smooth but the varying diameter may cause a problem when printing.
    e. Visual: Light contamination with a few warps. However, it does not look significant.
    f. Extrusion Temperature: 170°C
    g. Extrusion Observations and Notes: This filament was spooled when PLA chips that were shredded on the jointer (mixture of black, yellow, and red) were running out and additional pellets (manually cut white Hatchbox PLA chips) were added.

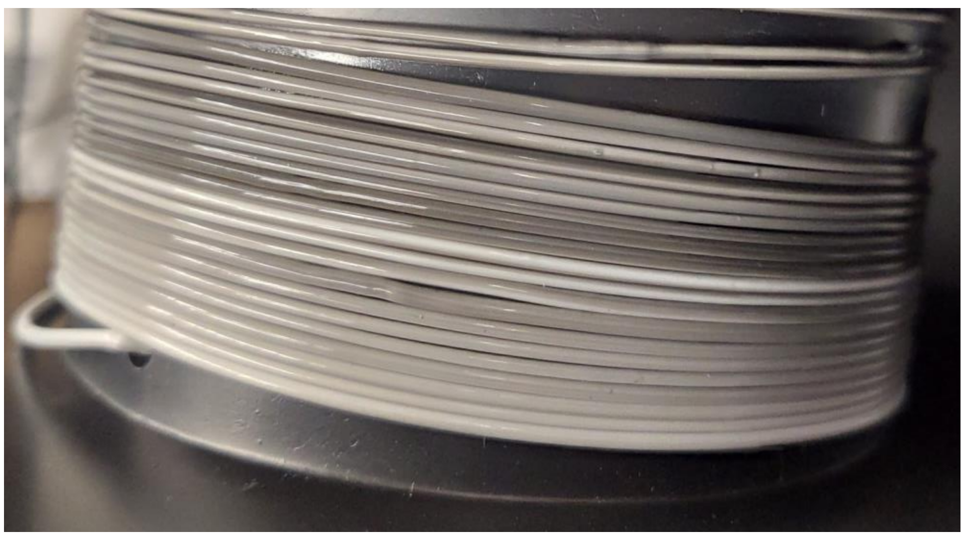

*Figure C.4: The spool mixes different colors as the color of the input changes over time.*

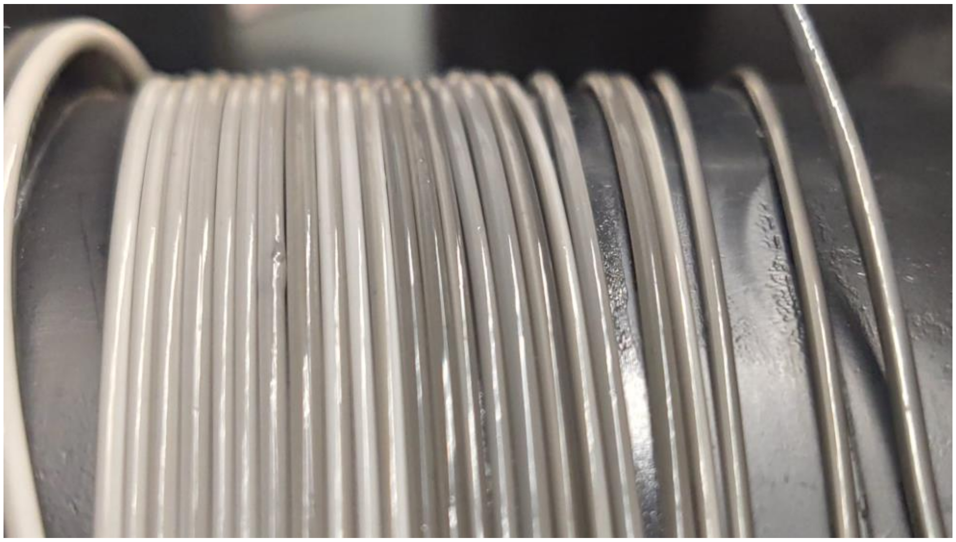

*Figure C.5: The filament has a smooth and glossy texture with a few imperfections visible.*

4. Filament 4
    a. Mass: 11 grams
    b. Color: Dark gray
    c. Diameter: 1.21-1.44 mm (Not very consistent)
    d. Printability: Not printable due to the brittleness, warps, and rough surface.
    e. Visual: The spool is not very smooth as some strands have warps and metal contaminants that do not look suitable for printing.
    f. Extrusion Temperature: 165-170°C
    g. Extrusion Observations and Notes: Filament extrusion transitioned from the black and white PLA chips that were shredded on the jointer to the white chips that were cut from a spool of PLA. The temperature was heightened from 165°C to 170°C during the process which led to the filament warping more but reduced the amount of unmelted PLA coming through the filament.

*Figure C.6: Varying diameters are visible from inconsistent extrusion.*

*Figure C.7: Filament color is evenly blended but exhibits unmelted PLA sections.*

5. Filament 5
    a. Mass: 15 grams
    b. Color: Black/Dark Gray
    c. Diameter: 1.55-1.7 mm (Consistent diameter)
    d. Printability: Printable but small warps in filament can jam the printer.
    e. Visual: It has a smooth texture with no unmelted parts. Slightly contaminated from outside dirt.
    f. Extrusion Temperature: 160-165°C
    g. Extrusion Observations and Notes: Used the dense and filtered black and yellow PLA chips and started to transition into the unfiltered black and white jointer and shredder chips. Started to raise temperature after unmelted sections started being extruded.

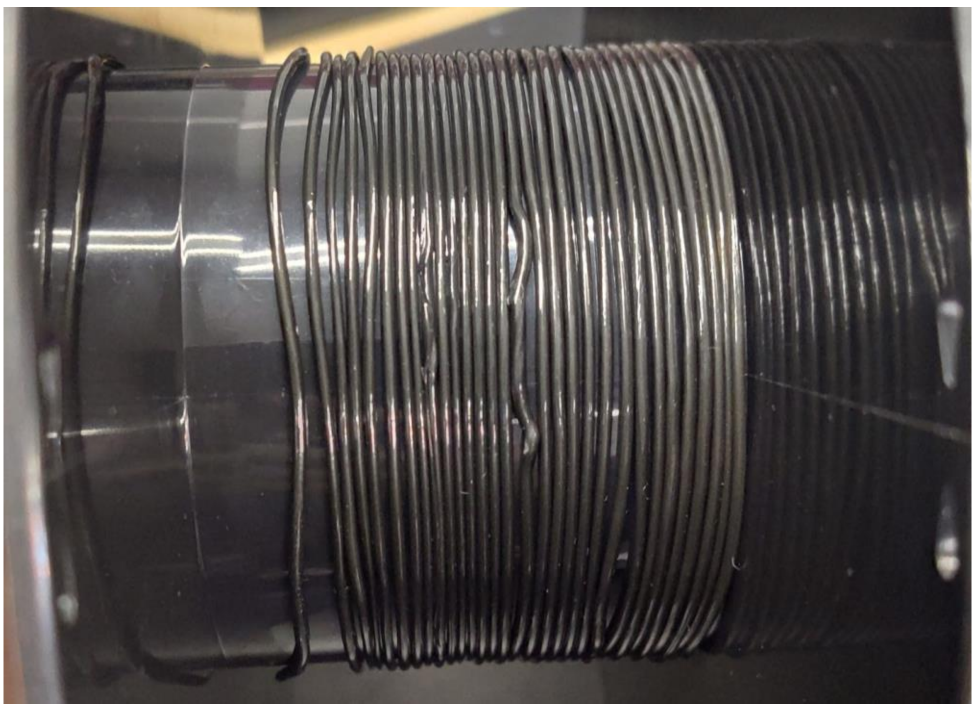

*Figure C.8: Filament exhibits a high gloss surface with significant warps in a few sections.*

*Figure C.9: Diameter and quality is consistent throughout the spool.*

6. Filament 6
    a. Mass: 17 grams
    b. Color: Black
    c. Diameter: 1.48-1.78 mm (Not perfectly consistent but a more accurate diameter)
    d. Printability: Looks visually printable. Some warpage is visible.
    e. Extrusion Temperature: 180°C
    f. Extrusion Observations and Notes: Can visually see some areas with warps and metal contaminants but it looks smooth throughout the filament. Used black and yellow dense chips to extrude with the FilaWinder in tandem. Chips are possibly thicker since the extrusion was suspended by the filawinder instead of being gravity fed to the ground.

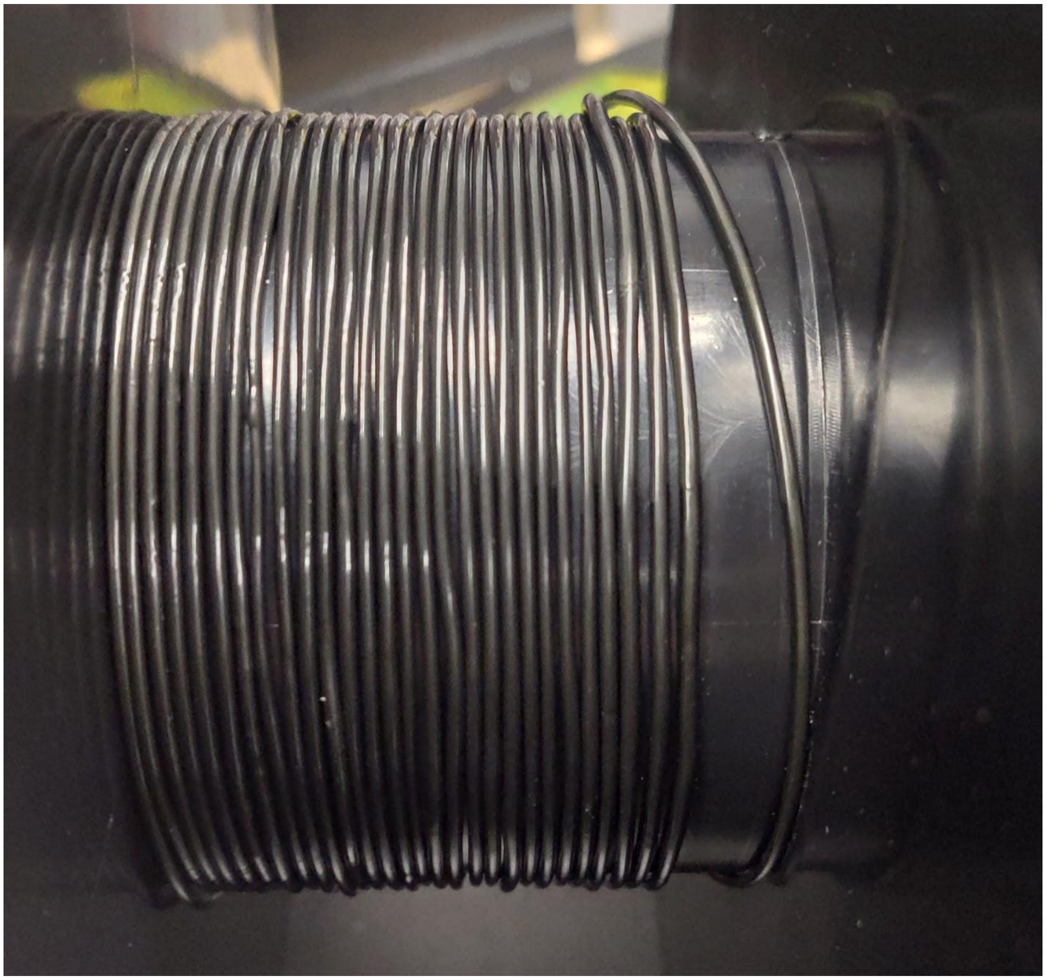

*Figure C.10: Diameter exhibits less warps and unmelted filament at a higher extrusion temperature.*

*Figure C.11: The spool has a very shiny surface.*

7. Filament 7
    a. Mass: 21 grams
    b. Color: Black to light maroon
    c. Diameter: 1.6 mm and below (Mostly consistent diameter and thickens over time)
    d. Printability: Looks visually printable.
    e. Visual: A few warps when the filament diameter starts to thicken.
    f. Extrusion Temperature: 180°C
    g. Extrusion Observations and Notes: Nice blend of color and smooth overall texture with a few contaminants. Used a mix of black, yellow, and red chips.

*Figure C.12: A consistent spool with a few significant warps*

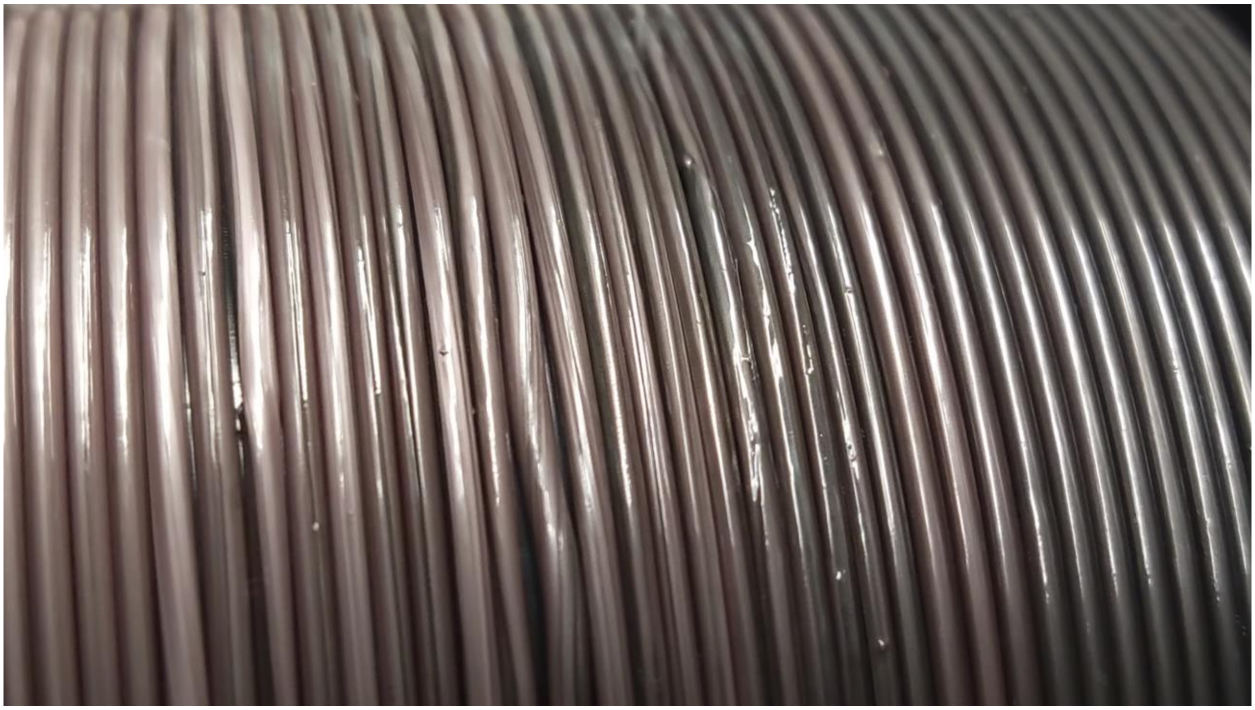

*Figure C.13: The blending of red and black chips is exhibited in the filament.*

8. Filament 8
    a. Mass: 61 grams
    b. Color: White/Gray
    c. Diameter: 1-1.5 mm and averaged 1.3 mm (Mostly consistent diameter and eventually thickens diameter)
    d. Printability: Looks printable.
    e. Visual: Minimum contamination with consistent texture and diameter extrusion.
    f. Extrusion Temperature: 170°C
    g. Extrusion Observations and Notes: Nice blend of color from leftover white PLA chips. Smooth overall texture and gravity fed to the ground.

*Figure C.14: The filament has a very consistent and uniform diameter and appearance with minimal flaws.*

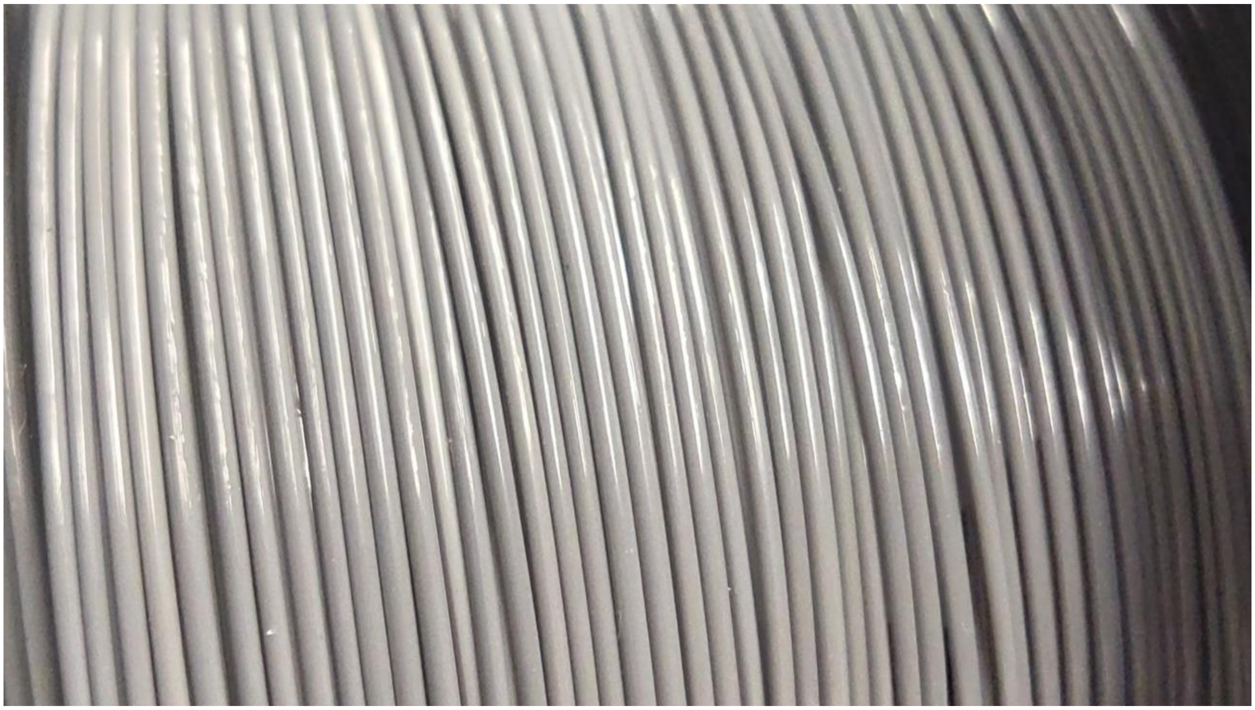

*Figure C.15: The color from the output is evenly blended and the strands are comparable to commercial filament.*

9. Filament 9
    a. Mass: 114 grams
    b. Color: Gray
    c. Diameter: 1.85 mm ± 0.25 mm
    d. Printability: Looks visually printable.
    e. Visual: A few warps when the filament diameter starts to thicken.
    f. Extrusion Temperature: 173°C
    g. Extrusion Observations and Notes: Smooth overall texture with a few contaminants. Used white and gray chips. The filament was wound with the FilaWinder as it was extruded.

*Figure C.16: The filament has a consistent diameter that is appropriate for 3D printing.*

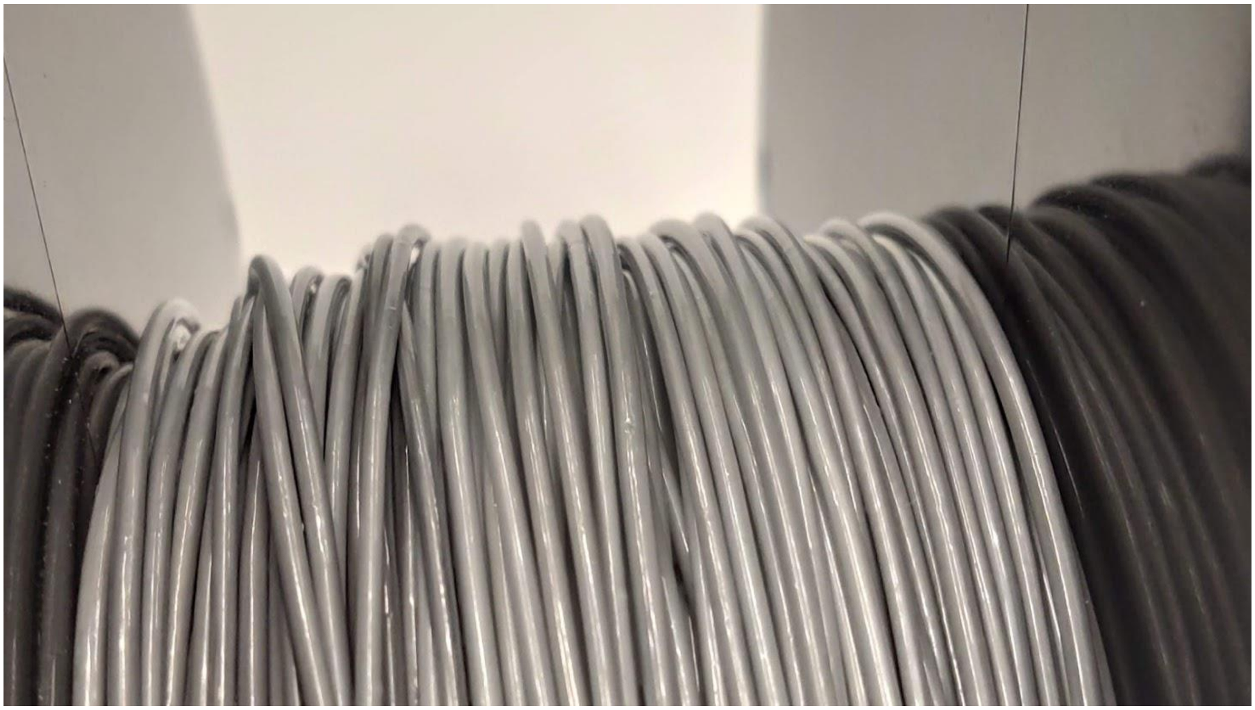

*Figure C.17: The filament is very glossy with minor imperfections visible.*

# Appendix D: Filament Diameters

*Table D-1: Recorded diameter measurements gravity-pulled filament extruded at 170°C.*

| Black and White Filament Diameter Measured Every Two Feet | | | | | |
|---|---|---|---|---|---|
| **Measurement #** | **Diameter (mm)** | **Measurement #** | **Diameter (mm)** | **Measurement #** | **Diameter (mm)** |
| 1 | 1.76 | 24 | 1.54 | 47 | 1.63 |
| 2 | 1.52 | 25 | 1.84 | 48 | 1.76 |
| 3 | 1.7 | 26 | 1.47 | 49 | 1.55 |
| 4 | 1.45 | 27 | 1.58 | 50 | 1.65 |
| 5 | 1.83 | 28 | 1.85 | 51 | 1.46 |
| 6 | 1.6 | 29 | 1.68 | 52 | 1.5 |
| 7 | 1.71 | 30 | 1.63 | 53 | 1.63 |
| 8 | 1.71 | 31 | 1.78 | 54 | 1.52 |
| 9 | 1.54 | 32 | 1.5 | 55 | 1.5 |
| 10 | 1.67 | 33 | 1.67 | 56 | 1.9 |
| 11 | 2.05 | 34 | 2 | 57 | 1.5 |
| 12 | 1.58 | 35 | 1.64 | 58 | 1.37 |
| 13 | 1.74 | 36 | 1.63 | 59 | 1.77 |
| 14 | 2.23 | 37 | 1.79 | 60 | 1.45 |
| 15 | 1.5 | 38 | 1.8 | 61 | 1.63 |
| 16 | 1.68 | 39 | 1.45 | 62 | 1.7 |
| 17 | 1.91 | 40 | 1.78 | 63 | 1.7 |
| 18 | 1.68 | 41 | 1.58 | 64 | 1.78 |
| 19 | 1.46 | 42 | 1.77 | 65 | 1.44 |
| 20 | 1.64 | 43 | 1.4 | 66 | 1.48 |
| 21 | 1.7 | 44 | 1.58 | 67 | 2.06 |
| 22 | 1.5 | 45 | 1.86 | | |
| 23 | 1.6 | 46 | 1.6 | | |

*Table D-2: Recorded diameter measurements FilaWinder-pulled filament extruded at 173°C.*

| Black and White Filament Diameter Measured Every One Feet | | | | | |
|---|---|---|---|---|---|
| **Measurement #** | **Diameter (mm)** | **Measurement #** | **Diameter (mm)** | **Measurement #** | **Diameter (mm)** |
| 1 | 2.1 | 26 | 1.82 | 51 | 1.83 |
| 2 | 2.12 | 27 | 1.73 | 52 | 1.84 |
| 3 | 1.96 | 28 | 1.72 | 53 | 1.64 |
| 4 | 1.95 | 29 | 1.73 | 54 | 1.67 |
| 5 | 1.88 | 30 | 1.78 | 55 | 1.8 |
| 6 | 1.88 | 31 | 1.74 | 56 | 1.78 |
| 7 | 1.92 | 32 | 1.73 | 57 | 1.7 |
| 8 | 1.98 | 33 | 1.8 | 58 | 1.77 |
| 9 | 1.89 | 34 | 1.75 | 59 | 1.77 |
| 10 | 1.87 | 35 | 1.8 | 60 | 1.83 |
| 11 | 1.84 | 36 | 1.69 | 61 | 1.62 |
| 12 | 1.8 | 37 | 1.77 | 62 | 1.87 |
| 13 | 1.83 | 38 | 1.83 | 63 | 2.02 |
| 14 | 1.75 | 39 | 1.67 | 64 | 1.55 |
| 15 | 1.8 | 40 | 1.74 | 65 | 1.68 |
| 16 | 1.88 | 41 | 1.82 | 66 | 1.99 |
| 17 | 1.75 | 42 | 1.75 | 67 | 1.75 |
| 18 | 1.74 | 43 | 1.69 | | |
| 19 | 1.8 | 44 | 1.83 | | |
| 20 | 1.77 | 45 | 1.77 | | |
| 21 | 1.82 | 46 | 1.6 | | |
| 22 | 1.8 | 47 | 1.8 | | |
| 23 | 1.6 | 48 | 1.82 | | |
| 24 | 1.75 | 49 | 1.7 | | |
| 25 | 1.75 | 50 | 1.75 | | |

# Appendix E: Longitudinal and Transverse Dogbone Specimens

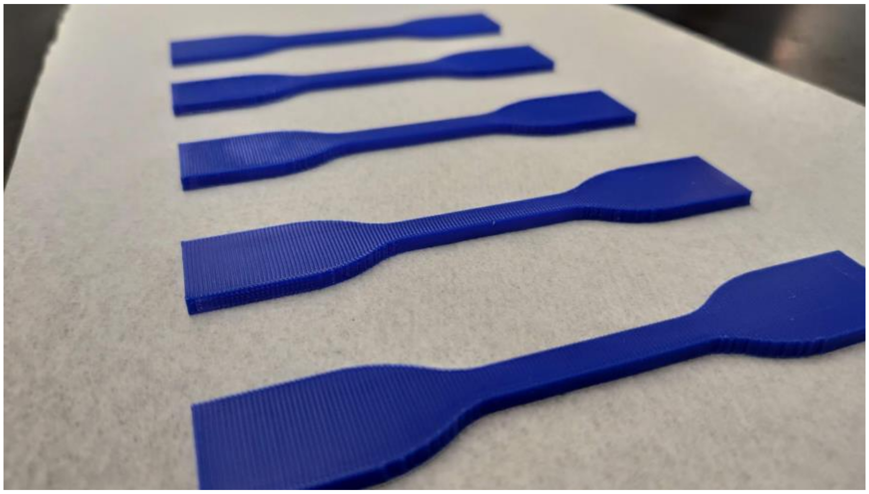

*Figure E.1: Transversal oriented dogbone specimen made from HatchBox filament.*

*Figure E.2: Longitudinal oriented dogbone specimen made from HatchBox filament.*