ENAC Semester Project
Sorting and shredding of plastic waste for the production by extrusion of 3D printers filament

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June 13, 2019

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Preface

I would like to thanks Doctor Yves Leterrier for the supervision of the project and the access to his laboratory. Big thanks also to Professor Anders Meibom, Samuel Cotture and all the technicians working at the SKIL for helping me realize the shredder. Thanks also to Stephen Poplineau who showed me the organization of the waste collection at EPFL and provided me with statistics.

Abstract

This report covers a semester project of the ENAC faculty at EPFL about the process of plastic waste to make filament for FDM 3D printing. The project starts by investigating which plastic commonly found in waste would be the most suitable for collecting, extruding and printing. Identification methods of plastics and mechanical performance of high-density polyethylene plastic are presented. An emphasis is put on the shredding step with the creation of a shredder based on the open-source model from precious plastic. Precious plastic is a non-profit project by Dave Hakkens promoting plastic recycling by freely giving tools and knowledge about plastic recycling. The shredder was then tested to see what results can be obtain and detect problems requiring improvement. Finally the fundamental principles of extrusion and fused deposition modeling are explained.

High-density polyethylene (HDPE) has been identify as the best plastic for the studied process. In the present state the shredder based on the precious plastic model would need a few improvements and the addition of an electrical motor to make it fully functional.

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1 Introduction

1.1 Background

The amount of plastic consumed every year is increasing since the 1950s and can be found today in a very wide variety of products. Plastic are used to make car components, food packaging, windows frame, prosthesis, phones and even spacecraft. We can obtain such a versatility with plastics mostly thanks to the different families of plastics and the addition of stabilizers, fillers, plasticizers and colorants. This way we can produce thousands of different plastics with the mechanical, physical and chemical properties corresponding to the intended use of every specific products.

Although those combinations are very convenient for production it makes the process of recycling very complicated. Most of the time trying to recycle different kind of plastic together is not possible because of incompatibility in between plastic families. Furthermore, other problem may arise during recycling with the abundant presence of additives or dirty and other material that are thrown away with plastics. For all of those reasons plastic sorting is an important and necessary part of the plastic recycling process.

Figure 1: Steps of PET recycling

After the sorting comes the step of shredding the plastic waste. This step is meant to reduce the size of the elements to make them more uniform in size and shape to facilitate the melting process. Size reduction is also necessary to accommodate for the melting equipment. For example, in the case of plastic extrusion for 3D printing filament the plastic chips have to go through an auger which as opening of a certain size (usually 1-2 cm) and can not take bigger chunk of plastic which gives the shredding requirement.

Before being melted the plastics are washed to remove as many dirty as possible. This process is done by specialized industrial plastic washing machine using mostly water. Once the plastics are clean they are melted down either to form pellets or filament.

Pellets are then used to create new products as they would be with new plastics.

1.2 Aims and objectives

The goal of this project is to have a look at the possibilities of recycling plastic waste at small scale for 3D with Fused deposition modeling printing.

The first step is to choose which thermoplastic to use for such a process and find out a way to identify plastic even if there is no visible ASTM sign.

In the second step we will have a look at is the shredding process with the creation of a shredder based on the precious plastic model.

For the last step we will see what could be done with the extrusion, printing and what kind of results could be expected with this process.

2 Choice of plastic convenient for 3D FDM printing

2.1 Availability of thermoplastic waste

The internationally adopted plastic classification (hereunder) is made by ASTM International, the American Society for Testing and Materials. This classification, despite being simplistic, allow for anyone to recognize the family of most plastic waste (based on the resin) with the simple reading of an icon. We will use it as a basis for the sorting in this project.

Figure 2: Description of ASTM icon for plastics

In Switzerland 1 million tons of plastic are consumed every year with only 17 percent of it being recycled. The main reason why we recycle so little plastic is because of the lack of sorting. Each of the above family have different melting temperature, mechanical properties, toxicity,... therefore they can not be recycled together.

PET is the only plastic sorted by the consumers consequently it is also the most recycled plastic with 37'451 tons out of the 45'340 tons consumed being recycled in 2017. There are no detailed statistics of the amount of the others plastic family consumed in Switzerland.

The situation is similar at the scale of the EPFL. In 2017 15.8 tons of PET and 55.9 tons of "other plastics" were collected. The collected PET is entirely recycled but in the 55.9 tons of "other plastics" only a tiny part is recycled when plastic films can easily be sorted. This is again due to the difficulty and cost of sorting the plastic for recycling once mixed. Non-recycled plastic is used as fuel.

2.2 Physical properties

For the intended process the plastics to be used are thermoplastics. Thermoplastic is plastic polymer material that get pliable at can be molded at some temperature and will solidify when cooling.

As mentioned in the previous chapter the most common families of thermoplastics found in trash are the following :

- Polyethylene terephthalate (PET)
- High-density Polyethylene (HDPE)
- Polyvinylidene chloride (PVC)
- Low-density Polyethylene (LDPE)
- Polypropylene (PP)
- Polystyrene (PS)

For fused deposition modeling the temperature of the melting point and the viscous behaviour is very important. Most of commercial 3D FDM printers can not heat the plastic above 300°C. For example the 3D printers in the SKIL laboratory at EPFL, Zortrax M200 Plus, can reach a maximum temperature of 290°C. For the process of producing filament it is also necessary to consider the properties of the extruder and the temperature the it reaches.
In addition, the melting point of the plastic shall not be considered as the maximum temperature the machines have to provide. The viscosity of the melted plastic being dependant of the temperature we might want to increase the temperature above the melting point to have a material fluid enough to work with.

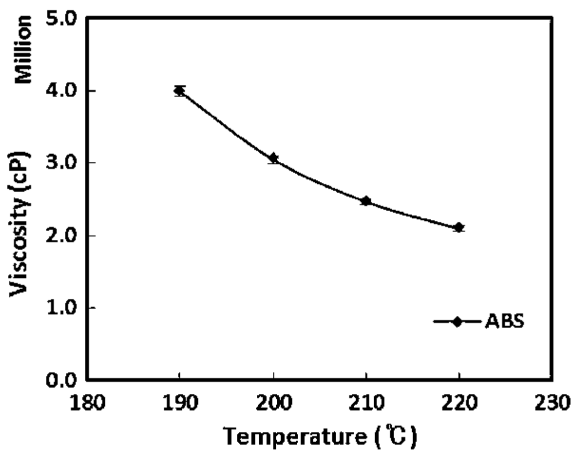

Figure 3: Viscosity of ABS function of temperature

Working above the melting point is also a good idea as the temperature is never uniform across all the material and trying to work at the limit will results in some chunks of plastic not entirely melting giving an heterogeneous product.

Table 11 Softening and Melting Ranges of Important Thermoplastics

Thermoplastic	Softening or Melting Range (°C)
Polyvinyl acetate	35–85
Polystyrene	70–115
Polyvinyl chloride	75–90 (softens)
Polyethylene, density 0.92 g/cm^3	about 110
density 0.94 g/cm^3	about 120
density 0.96 g/cm^3	about 135
Polybutene-1	125–135
Polyvinylidene chloride	115–140 (softens)
Polymethyl methacrylate	120–160
Cellulose acetate	125–175
Polyacrylonitrile	130–150 (softens)
Polyoxymethylene	165–185
Polypropylene	160–170
Nylon 12	170–180
Nylon 11	180–190
Polytrifluorochloroethylene	200–220
Nylon 6, 10	210–220
Nylon 6	215–225
Polybutylene terephthalate	220–230
Polycarbonate	220–230
Polyethersulfone	228–230
Poly-4-methylpentene-1	230–240
Nylon 6, 6	250–260
Polyethylene terephthalate	250–260
Polyphenylene sulfide	260–280
Polyarylether ketone	340–380

Figure 4: Melting range of thermoplastics

In the above table we can see the melting temperature of thermoplastics. Thanks to it we can discard the use of Polyethylene terephthalate (PET) for our recycling process as its melting temperature is close to the limit of our machines. With regards to temperature and availability Polyvinylidene chloride (PVC) looks like a good candidate but is not suitable because PVC is corrosive, so might damage the extruder and printer, and when burned it emits hydrogen chloride fumes which are toxic. Polystyrene waste, mostly found in the form of foam, is difficult to manipulate and shred in large enough amount because of its very low density and would need to be compacted beforehand.

In the end the most convenient plastic for shredding, extrusion and 3D printing is high-density polyethylene (HDPE). Its melting temperature of 135 is suitable for use in commercial extruder and 3D printers, its fumes are not toxic and it can easily be identified and manipulated.

2.3 Identification and collection of HDPE

In form of bottle HDPE is easily recognizable. Hereunder are two container of "other plastics" at EPFL. We can see in both images bottles in HDPE.

Figure 5: "Other plastics" container at EPFL

To automate the identification and sorting of plastic Near Infrared Reflectance Spectroscopy can be used. This identification method is based on the principle that light of wavelengths between 750μm and 1 mm causes molecules to vibrate. These vibrations varies depending on the material therefore an absorption spectrum specific to each plastic can be established.

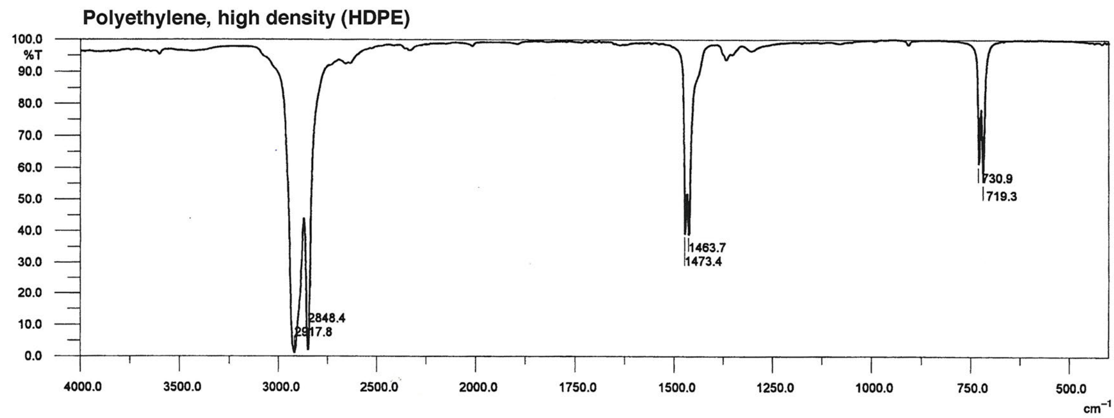

Figure 6: IR absorption spectrum of HDPE

A way to classify plastic with no access to an ASTM icon or NIR machines is the flame test. It is a very easy to realize test based on empirical observations. The flame test is based on the burning, melting behaviour and odor of plastic. This test is very convenient but not as reliable as the NIR identification and can be disrupted by high presence of additives in the plastic. HDPE is easily recognizable with the flame test thanks to its burning behviour alike the one of a candle.

Figure 7: Flame test with HDPE

The table hereunder provides an exemple of this method.

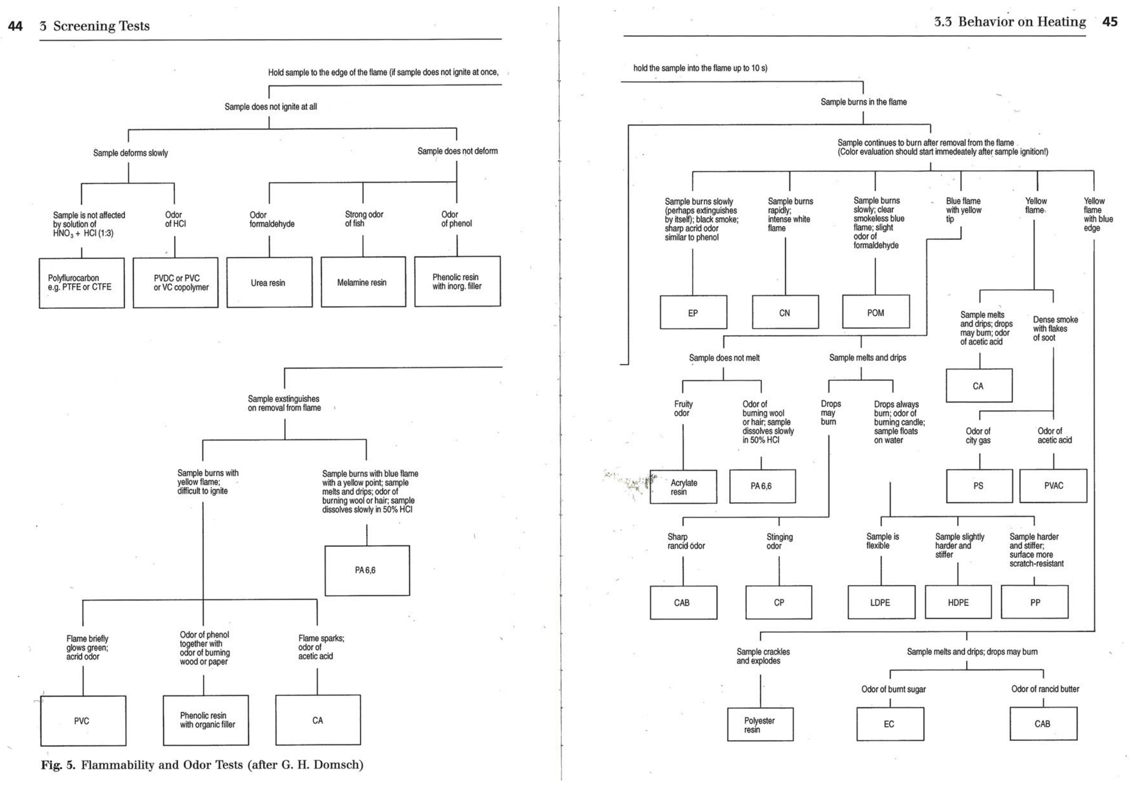

Figure 8: Flame test after G. H. Domsch

2.4 Mechanical properties of recycled HDPE

Haruna Hamod, student of ARCADA university, has done experiments on recycled HDPE to determinate its mechanical properties and compared it with ABS, PLA and new HDPE. The recycling steps done are the same as the ones described in this project but the tested element was molded instead of printed. The results he obtained are the following :

Table 7 Comparison table for 3D filament

Tests	PLA	ABS	Tested HDPE (Mean Value)	Tested rHDPE (Mean Value)
Melt index (g/10min)	2.4 – 4.3	22- 48	3,37	2,85
Tensile Strength (MPa)	50 - 55	30 - 52	25,45	25,59
Young's modulus (MPa)	3500	1700 – 2800	463,35	428,38
Strain at Yield (%)	10 - 100	3 – 75	16,12	16,12
Melting temperature (^{0}C)	120 - 190	200 - 230	190	190
Extruding Temperature (^{o}C)	160 – 220	210- 230	190	160 - 190

Figure 9: Mechanical test on molded elements with ABS, PLA, HDPE and recycled HDPE

We see that the recycled HDPE has slightly lower properties than the new HDPE but they stay very similar. One property that did significantly change with recycling is the viscosity. The recycled HDPE is less fluid than the new one. Compare to ABS and PLA HDPE has lower mechanical performance.

3 Plastic shredding

3.1 Purpose of shredding

The step of shredding is essential for several reasons.

Shredding of plastic waste allow to reduce elements of various shape and size to a homogeneous mixture easier to manipulate.

If plastic waste cleaning is done by hand it easier to do it before shredding but in order to automate this step preliminary shredding is necessary as dealing with elements of various size in automation is very difficult.

The shredding is also necessary for the extrusion step. The auger of any extruder has a limit size of plastic chunk it can handle. Plastic chunk bigger than that size could block the machine. Also having small elements allows for a more uniform heating and better filament.

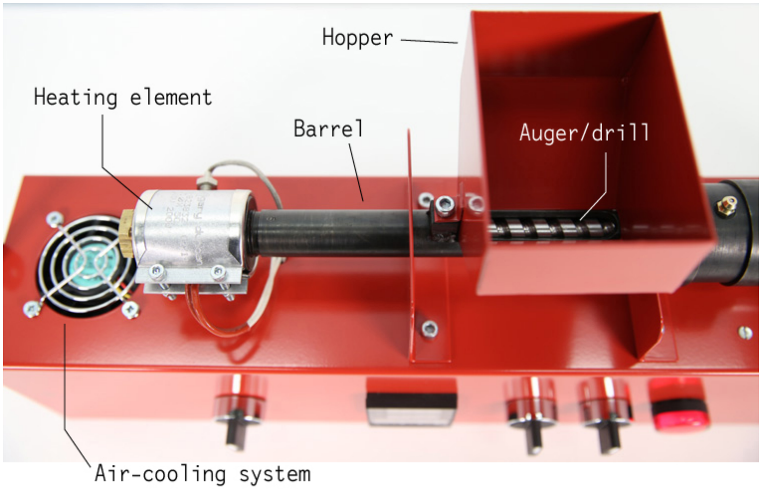

Figure 10: Noztek Pro commercial extruder

3.2 Creation of a shredder based on the precious plastic model

Commercial plastic shredders being expensive we built our own shredder based on the model of precious plastic. We began by downloading the open source 3D model available on the Precious Plastic website. The 3D model was modified to simplify the cutting of steel and cutting plans of the parts to be machined were made.

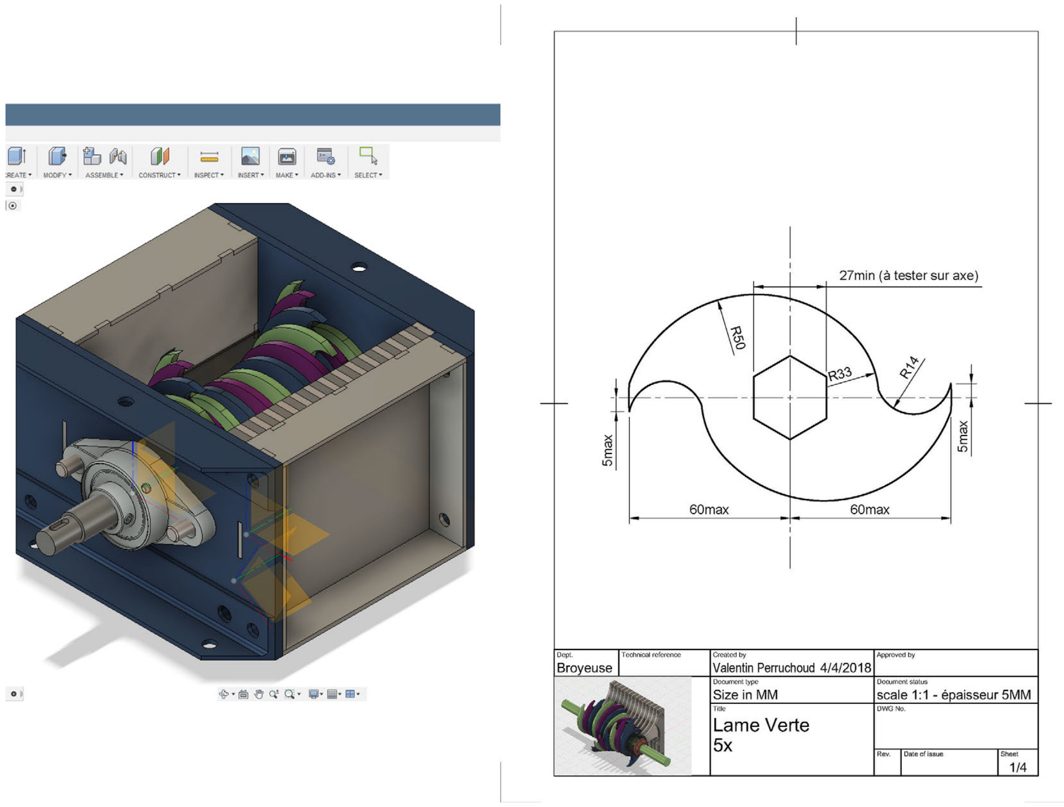

Figure 11: 3D model of the shredder and cutting plan of one knife

Those plans were then sent to an EPFL workshop for the cutting of the steel plates. Once the cutting done the assembly of the parts was done at the SKIL. The force required to operate the shredder being unknown a handle was build using scrap material to do some testing. The handle was connected to the shaft with a Taperlock system squeezing the shaft to hold using friction. A Hoper was made with MDF plates cut by a laser cutter. This Hoper guides the plastic when feeding the shredder and makes the operation safer.

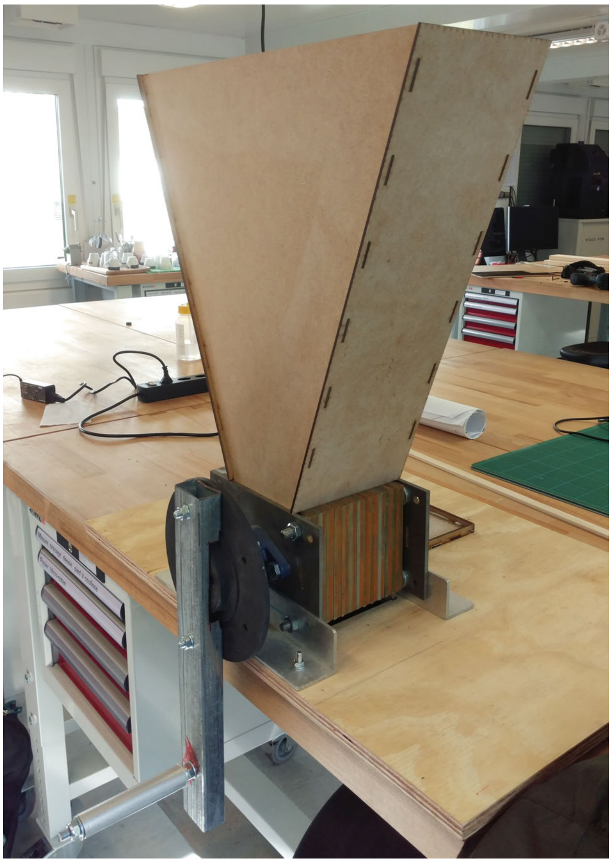

Figure 12: Build of the shredder completed with Hoper and handle

3.3 Test of the shredder

To estimate the size of the plastic chunks that could be obtained with our shredder we shredded PET bottles and obtained the following results for the material going through the knives.

Figure 13: Shredding product of PET bottles

The chunks obtained are under 2 cm long and about 6 mm wide which correspond to the space in between the knives. Such a size is too large for extruders such as the Noztek Pro but is working with extruders with a larger auger like the one of precious plastic.

An issue we have with this shredder is the spacing in the places shown in red in the picture hereunder. The problem of the space on the left could be solved by adding to the hoper a piece filling the gaps forcing the plastic to hit the knives. The spacing with the nut could be solved by tapping the lateral plate and screwing a shorter bolt directly into it (bolt holding the bearing).

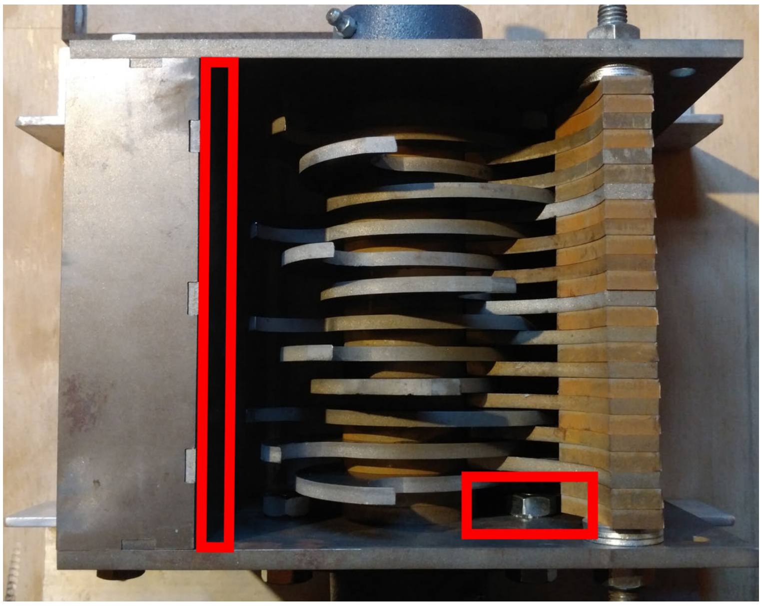

Figure 14: Holes in the shredder allowing chunk of plastic to fall without being shredded

Due above-mentioned holes we have plastic chunk with the size shown in the image below falling with the properly shredded pieces.

Figure 15: Chunks of plastic falling without being shredded

An other problem we had was the resistance of the Taperlock connection between the shaft and the handle. As the connection is made by friction only it is sufficient when shredding thin plastic such as PET bottles but it is insufficient for thicker plastics such as bottle caps in HDPE. By blocking the knives with a piece of wood and applying a weight on the handle we found a resistant torque force of 70 [Nm]. (Lever arm of 0.25 [m] and 28 [kg]). This resistance could be greatly improved by machining a pin connection on the shaft.

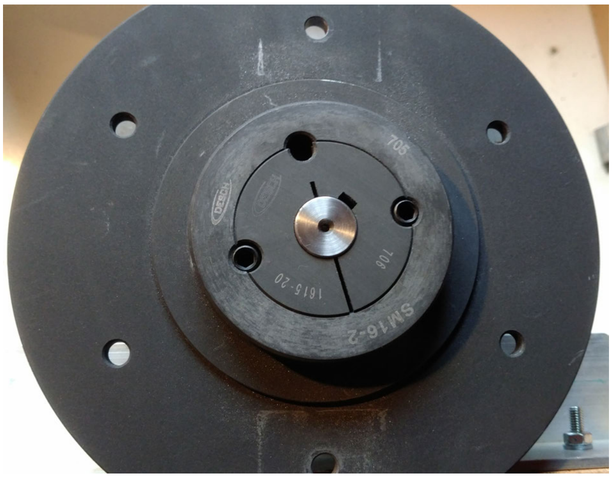

Figure 16: Taperlock connection

4 Working principles of extrusion and 3D printing

4.1 Operating principle of an extruder

An extruder is a machine taking small chunk of a material, melting it and pushing it through a hole with a shape corresponding to the planned geometry of the new object. Hereunder is a cross-section of a typical extruder explaining its functioning.

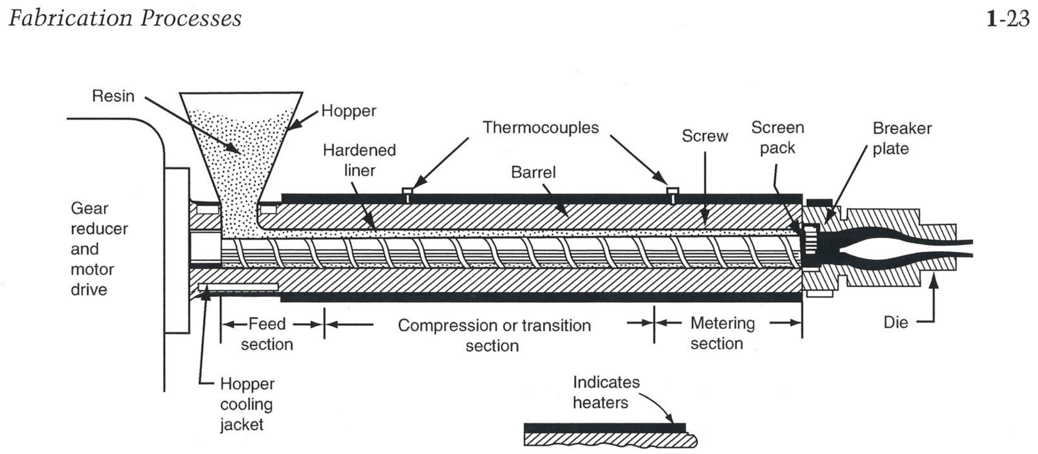

Figure 17: Cross-section of a standard extruder

The plastic is fed in the extruder via the hopper. At the bottom of the hopper is a auger pushing the material. As the material moves forward in the tube, it heats up and melts. At the end of the tube is a die giving its shape to the filament that cools and solidify when leaving the die.

4.2 Operating principle of fused deposition modeling 3D printing

The principle of FDM 3D printing is very simple and works in a similar way to the extruder used to produce the filament.

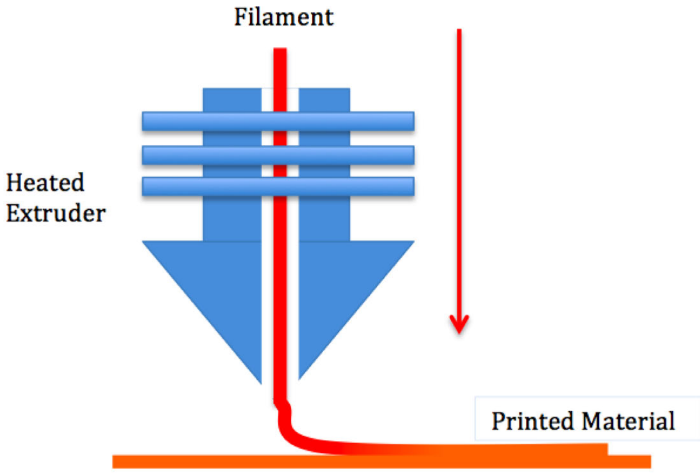

Figure 18: Diagram of fused deposition modeling principle

The filament is fed to the printing head with a small electrical motor. In the printing head the filament is heated to its melting point. The viscous and hot plastic leaving the moving printing head is deposited accordingly to the instructions of the 3D CAD model and the element is printed layer by layer using this process. With this production process the produced element does not have isotropic mechanical properties. The connection in between the layers is a weak point.

5 Conclusion

In this semester project we did an overview of the complete recycling process from high-density polyethylene plastic waste to 3D printer filament with an emphasis on the shredding part.

As can be seen, this recycling process is technically feasible but not economically viable at large scale. Today the sorting of plastics other than PET by the consumer is non-existent in Switzerland. There is also no method of industrial sorting implemented because there is no big company that could do the collecting and sorting of plastic at a national scale which would make the process profitable.

The assembly and testing of the shredder has shown that the shredding is working but some improvement are needed to make it fully functional with a big one being the addition of an electrical motor capable of delivering a lot more torque than 70 [Nm] and a pin connection to the shaft. The testing also revealed the importance of considering the transition from one stage to the other as chunk of plastic we are producing are too big for use in the intended extruder.

The best plastic to be used for recycling as 3D printer filament is high-density polyethylene for the ease of the process. The mechanical properties obtained with this material are lower than the one of PLA or ABS but is sufficient for prototyping.

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