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Design and Development of Plastic Filament Extruder for 3D Printing

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ABSTRACT

3D printing is a form of additive manufacturing technology where a three dimensional object is created by laying down successive layers of material. It is mechanized method whereby 3D objects are quickly made on a reasonably sized machine connected to a computer containing blueprints for the object. As 3D printing is growing fast and giving a boost to product development, the factories doing 3D printing need to continuously meet the printing requirements and maintain an adequate amount of inventory of the filament. As the manufactures have to buy these filaments from various vendors, the cost of 3D printing increases. To overcome the problem faced by the manufacturers, small workshop owners, the need of 3D filament making machine arises. This project focuses on designing and fabricating a portable fused deposition 3D printer filament making machine with cheap and easily available components to draw 1.75 mm diameter ABS filament

Keywords: ABS, 3D printing, Extrusion, Single Screw Extruder

Introduction

Due to the large scope of 3D printing this technology has experienced in the recent decades a great development. The access to 3D printers is becoming easier as the prizes are going down. Nowadays both companies and regular users can develop their own parts in a relatively simple and quickly way. That is why there is more and more interest in evolving this technology which has already revolutionized manufacturing processes.

Today there are plenty options when choosing a printer and a lot of different companies that manufacture and sell these printers. But most of the 3D printer is based on the fused Deposition Method, which uses mostly PLA and ABS as the printer material. This extrusion based 3D printer uses a wired filament of diameter 1.75mm or 3mm for printing. So most of the manufacturing units, companies, colleges who have the 3D printer in-house are dependent on 3rd party supplier, and need to buy the 3D printer filament from these suppliers.

This paper will make you go through the design and development of a portable 3D printer filament making machine for small manufacturing units and colleges.

The new designed portable filament making machine should be able to make the wired filament from the plastic granules.

With the development of the portable filament making machine, the dependency of the manufacturing units and other organization on 3rd party supplier for filament will be reduced.

Objectives

1. To design and develop a plastic filament extruder for 3D printing
2. The focus was specifically on creating 1.75 mm diameter filament from ABS pellets.
3. To develop a 3D printing filament making extruder that can be used by small scale manufacturing units, companies, colleges who have portable 3D printer in-house.
4. To Perform design calculations to base the development of filament making extruder

Motivation

3D printing is growing technology and is used worldwide. 3D printing requires filament to process and the cost of filament governs the cost of 3D printing product. Filament extrusion machines are usually available for industrial use, capable of creating hundreds of feet of long filament in a day. So these filaments are expensive for many end users.

This work will make easily available filament extruder to small scale industries and colleges.

Option of Design

Horizontal 3D filament making machine

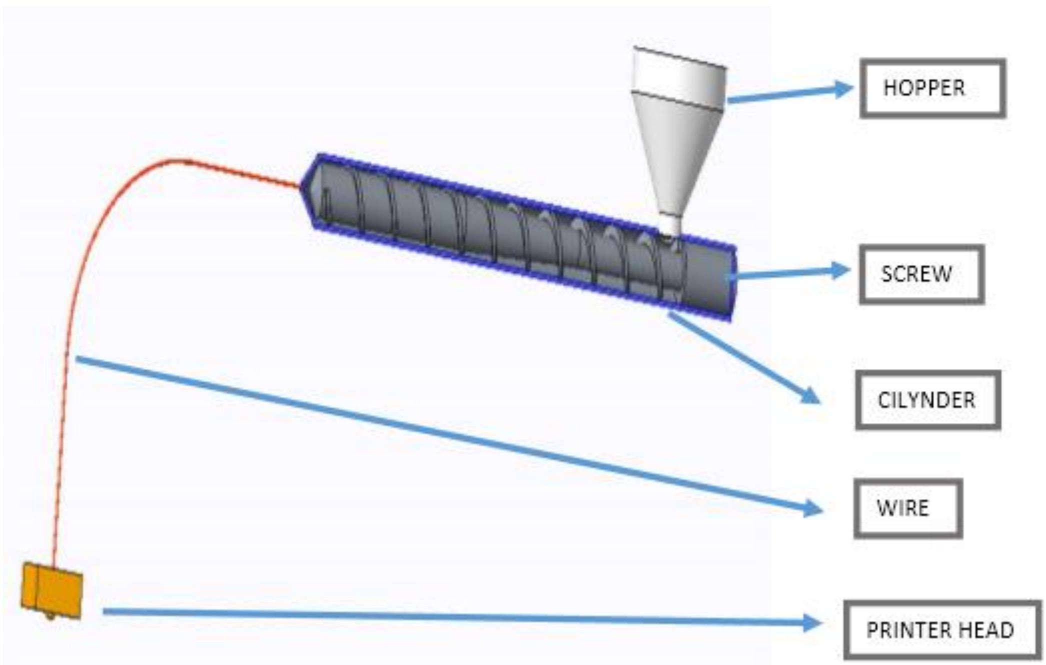

Figure 1 Horizontal 3D filament making machine

Most 3D printers use a wire as feed material, so the first option is to develop an extruder that permits the manufacture of the wire. This allows us to start the process of printing from plastic granulate.

The process starts feeding the hopper with the plastic. The screw drags and breaks granulate. The extrusion process continues until the material comes out of the nozzle creating he wire which will be guide by a plastic tube into the printer´s head.

Apparently this option is the simplest one but there are some problems to be solved. The biggest problem is when the extruder stops working all the plastic inside the canal lowers its temperature and solidifies. So is not possible to start the process again. Furthermore, as the wire comes out with a high temperature and in a melted way, the material gets stuck into the tubes walls and the printing process is not uniform and it can block the tube.

Advantage
Easy design

Problems/disadvantages:
When the process is stopped, the plastic in the tube that connects the extruder solidifies. This makes impossible to start another impression. As the plastic comes out at a very high temperature of the extruder, it could stay stuck in the tube walls

Equipment Description

Screw

There are two basic characteristics that the screw should satisfy in order to perform his function correctly. It has to be hard enough to bear with the possible erosion and to be able to handle with high temperatures.

The high temperatures will be caused by the movement that the screw has, the friction against the cylinder and the heating system.

The material chosen for the screw is steel F-174, which is a nitriding steel. This material is typically used in extruders screws and cylinders and reaches a vickers hardness of 1048-1064 HV. In addition, it is able to handle with the high temperatures reached inside the extruder, which will be around 200ºC. Steel pieces which have been treated with a nitriding process are usually prepared to stand temperatures up to 500ºC. Also the nitriding process gives the piece an extra layer of protection against the corrosion.

For the properly development of the extrusion process it is necessary that the screw surface is as smooth as possible, to avoid friction and to allow the plastic slide on it.

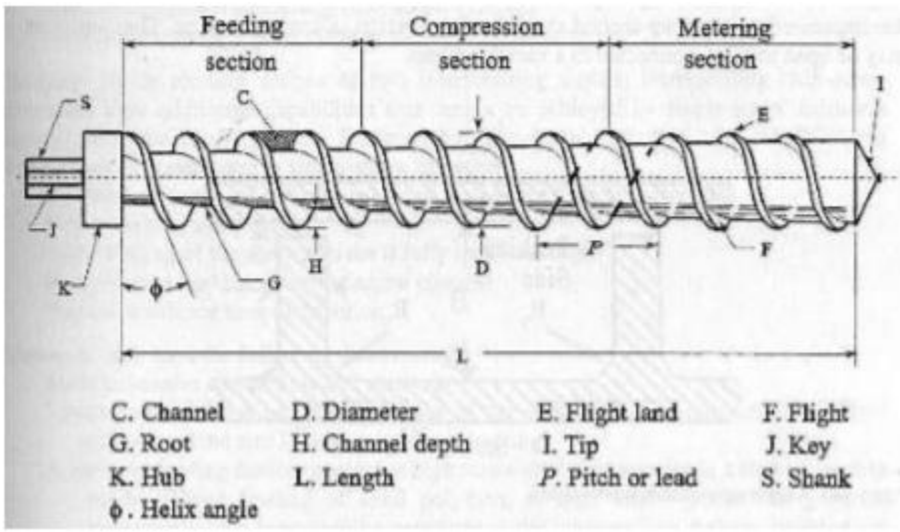

Figure 2 Screw Geometry details

The diameter we decide to work with is 25 mm and for the relation between the length and the diameter we choose, 12/1. The reasons to take these measures and not any others are based basically on the fact that the screw has to be the smallest size possible without increasing very much the price. So we consider 25 mm to be the smallest diameter with reasonable price and with precise usefulness. In addition, we choose 12/1 for the relation L/D because we consider 300 mm the maximum length keeping a light screw in terms of weight, taking into account that if the relation L/D is bigger, the price will be lower.

Therefore, I have defined the first parameters of our screw D =25 and L=300. Also they have been taken into account other options of diameters and length.

Number of channels

The first step to be taken in the process of design a screw is deciding the number of channels on it that is, deciding the number of threads. In applications where a large flow is required, screws can be used with two or more threads, but in our case the flow is very small so we will use a screw with a single thread. So the number of channels for our extruder m=1.

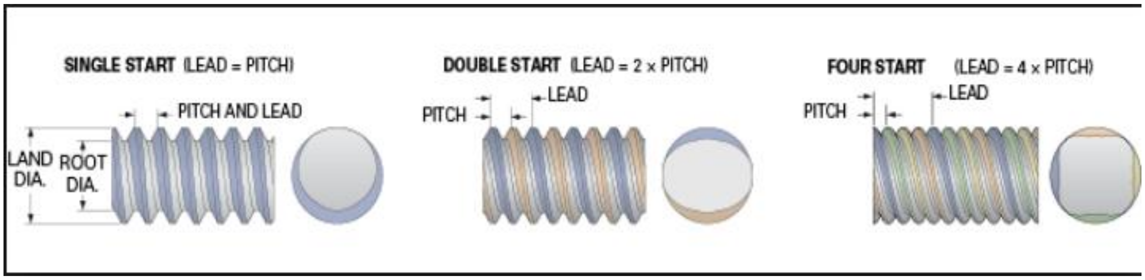

Figure 3 Number of channels of Screw

Helix Angle

Also one of the first things we can determine of our extruder is the helix angle of the screw. For general purpose screws, the gap between 2 crests or the pitch (t) usually coincides with the diameter. So

$$t=D=25mm$$

So the helix angle is

$$\varphi = \tan^{-1} \frac{t}{\pi D}$$

$$\varphi = \tan^{-1} \frac{25}{\pi * 25}$$

$$\varphi = 17.65^{o}$$

Ridge width

The width of the ridge is defined by the diameter of the screw as it exists a relation between them, $e=0.12*D$

So e= .12*25

e = 3 mm

Screw lengths

For amorphous thermoplastic, the feeding zone is between 20% and 25% of the screw length, the compression zone between 32% and 38% and for the metering zone between 40% and 45% .

We based our decision of the zones lengths on the percentage from the total length that normally has each zone.

The percentages used in each zone are obtained as follows:

$$\% = \frac{\%}{\%1+\%2+\%3}$$

$$L1\ \% = \frac{20}{20+32+40} = 0.217$$

$$L2\% = \frac{32}{20+32+40} = 0.348$$

$$L3\% = \frac{40}{20+32+40} = 0.435$$

Feeding Zone Length: L1 = 0.217 * 300 = 65mm

Compression Zone Length: L2 = 0.348 * 300 = 105mm

Metering Zone Length: L3 = 0.435 * 300 = 130mm

Channel depth and screw clearances

The clearances inside the screw and with the cylinder are also defined by the diameter I have chosen.
The channel depth h1, is the space between the cylinder and the soul of the screw. It is related with the screw diameter with the equation

$$h1 = 0.2 * D$$

$$h1 = 5\ mm$$

The filet clearance is the space between the thread and the interior surface of the cylinder. It should be small enough to avoid the plastic to come back while extruding.

The equation to calculate it is:

$$\delta = 0.002 * D$$

$$\delta = 0.05mm$$

The depth of the channel at the end of the screw is defined by the compression ratio (Z). The compression ratio relates the depth of the channel at the beginning and at the end of the screw.

Barrel or Cylinder

Just as for the screw, the material chosen for the cylinder is steel F-174, for the same reasons. The cylinder must also be able to handle with high temperatures and be hard enough to resist degradation due to the friction generated between the inner face of the cylinder and the plastic flow.

The cylinder is the part in charge of keeping the material inside while going throughout the screw. For this reason, its inner diameter is the sum of the screw diameter and the clearance calculated above, to a total of 25.05 mm.

Considering tolerance and according to the availability of standard tube, 1” ID tube meets our requirement, so we have selected 1”ID tube for the cylinder.

Barrel Extension

Barrel Extension material is same as Barrel for the same reasons. It is manufactured by turning operation. It is welded to the end of the Barrel. This extension is used to couple barrel piece to die and to give sufficient thickness to fit the secondary heater.

In addition, 4 mm thick aluminum strainer is attached to smoothen the flow and 3/8” nut to control the flow.

Die or Nozzle

The material most commonly used for die is brass because it has to withstand high temperatures. Likewise, is a good conductor of heat, quality that is needed to heat fast and uniform the nozzle as the printing material needs to be printed around 200ºC. Brass is one of the material with best characteristics and this is why we are choosing it for the nozzle. The nozzle is also one of the most important elements of extruder, as it defines the final shape of the plastic. Between its characteristics we are going to remark its hardness and the fact that it perfectly keeps its conditions for a long period of time. Also, it doesn't get affected by the external conditions. Its characteristics make it one of the best materials in the market but with a lower price. The die that is used is M12 Brass plug with 2mm hole.

Hopper

Hopper is made up of stainless steel sheet metal.

There are no specifications for hopper design. Its size varies depending on the application or quantity of production. So the hopper design is just to fulfill the requirement of this project.

Hopper is designed as gravity fed hopper. Hopper is wedge type and the flow of solid in the hopper is mass flow. It is cut and manufactured from 6”x4”

Motor

The motor for the system is a 55 RPM motor with stall torque of 53 lb-in (61 kg-cm).This motor is controlled by a PWM (Pulse Width Modulation) speed controller. This controller is wired in series with the power source from 24 V supply and the motor. This was the simplest control system. It is a variable speed control system with the RPM is selected by varying the duty cycle

Heater system design

Heaters are located along the barrel, with thermocouples in each zone to control the heaters and barrel temperature. The heaters cover as much barrel surface area as practical, minimizing hot and cold spots along the barrel length. In an individual extruder temperature zone, there may be one, two, or three heater bands with one thermocouple controlling them. Assume the heater band closest to the thermocouple burns out; the other two heater bands have to supply all the external energy required, creating the possibility that the area is hotter near the two heater bands that are working. In the event, the band farthest from the thermocouple burns out, the barrel area under the burnt-out heater is anticipated to be cooler than areas where the heaters are functioning properly near the controlling thermocouple. Burnt-out heater bands should be replaced as soon as possible to assure uniform heat input.

Temperature Zone Control

Each extruder temperature zone has at least one heater and possibly multiple heaters controlled by a thermocouple. A signal from the thermocouple communicates with the controller, indicating whether the heater is to be turned on or off. For the controller and heaters to function properly, the thermocouple must operate properly. A faulty thermocouple with an open circuit indicates the temperature is low, resulting in the heaters staying on and causing substantial overheating. A closed thermocouple indicates the temperature is high; heaters remain off and the temperature zone cools. If a thermocouple is not responding properly, it must be replaced.

The thermocouple well in the barrel should be at least 1.2 inches (30 mm) deep and installed away from the heaters. Never sandwich the thermocouple between the heater and the barrel wall; the thermocouple will be responsive to the heater temperature and not the barrel temperature.
We have used 35 x 30 mm, 150 Watt heating band.

Fixing system

What we have called fixing system; it is nothing but the pieces we have designed to set our extruder. This fixation system is responsible for holding the extruder and the rest of the pieces. In addition, the fixing system will hold the fans that cool the filament coming out of die.. Therefore, the pieces we have to design should perform simultaneously three different functions. To start designing the pieces we look at the extruder which we are going to assemble. In addition, the heater system is designed in a way so that the fixing system has to be allocated between both of the heater pieces. So we have designed the fixing system that will cover all the extruder parts. We have used Mild steel square-shaped tube for fixing system designed.

EXTRUDER PRODUCTION CALCULATIONS

Volumetric Flow

Production expressed as volumetric flow, Q, is the result of three different types of flow.
A) Drag flow is the largest component caused by turning the screw.
B) Pressure flow, is the component that opposes the flow system. Flow filtration is produced by the loss of material between the clearances of the screw cylinder.
The volumetric flow Q can be calculated with this equation:

$$Q = \left(\frac{\alpha K}{K+\gamma+\beta}\right) \eta$$

Where:

Drag flow coefficient: α

Pressure flow coefficient: β

Filtration flow coefficient: γ
Head geometrical constant: K
Spindle speed: η

Drag Flow Coefficient
The Drag flow is the component caused by the turning screw. The plastic enclosed between the spindle and the cylinder is forced to advance in axial direction. It can be calculated with this equation:

$$\alpha = \frac{\pi * m * D * h * \left(\frac{t}{m} - e\right) * Cos^2 \phi}{2}$$

Where:
Screw diameter: D=25mm.
Pitch: t=25mm.
Initial channel depth: h1=5mm.
Helix angle: ϕ =17.65.
Ridge width: e=3
Number of channels m= 1.
Thereupon the drag flow we will have:

$$\alpha = 3922.57 \text{ mm3 or } 3.92\text{cm3}$$

Pressure Flow Coefficient
Pressure flows appears against the main flow. It is very important to design properly the screw so the pressure flow is lower that the drag flow, otherwise the extruder won't have any production flow.

$$\beta = \frac{m * h^3 * \left(\frac{t}{m} - e\right) * sin\phi * \cos\phi}{12 * L}$$

Where:
Screw length: L= 300mm
The rest of the parameters are the same that the ones we used to calculate the drag flow coefficient.

$$\beta = .2207 \text{ mm3 or } 2.209 * 10^{-4} \text{ cm3}$$

Filtration Flow Coefficient
The filtration flow coefficient represents the portion of fluid that seeps between the crest of the screw and the cylinder wall.

$$\gamma = \frac{\pi^2 * D^2 * \delta^3 * \tan\phi}{10 * e * L}$$

Where:
Filet clearance: δ =0.05mm
The rest of the parameters are the same as the previous ones

$$\gamma = 2.725 * 10^{-05} \text{ mm3 or } 2.7258 * 10^{-8}\text{cm3}$$

5.1.4 Head Geometrical Constant
d0=D−2∗h= 12mm (here D is nozzle outer diameter)
d1= 2mm

To determine the constant K, the head is divided into successive zones of different settings, setting for each of these areas a different constant ki. The head is dividing in two different zones, one conical and the other one cylindrical.

To the conical section:

$$k_1 = \frac{3 * \pi * d1^3 * d0^3}{128 * L * (d1^2 + d1 * d0 + d0^2)}$$

And

To the Cylindrical Section

$$k2 = \frac{\pi * d^4}{128 * L}$$

Since the nozzle for the extruder is being made manually from a 0.5 inch threaded brass plug. So it is in a cylindrical shape, so we will only calculate the Cylindrical Section.

That is the

L is the length of the nozzle, which is 25 mm or 2.5 cm

k2 = 0.03195

So the geometrical constant K is 0.03195

Screw Turning Speed and Flow Rate

Since the max rated RPM of the motor is 55, considering a factor of safety of 2.

Let the speed of the screw be 30 RPM

$$Q = \left(\frac{\alpha * K}{K + \gamma + \beta}\right)\eta$$

$$\eta = \frac{Q}{\frac{\alpha * K}{K + \gamma + \beta}}$$

Where

Flow rate: Q

Drag flow coefficient: α = 2008.35mm3

Pressure flow coefficient: β = 5.650 *10-3 mm3

Filtration flow coefficient: γ = 1.11 ∗ 10-05 mm3

Head geometrical constant: K = 0.03195

$$Q = \left(\frac{3922.57 * 0.03195}{0.03195 + 2.725 * 10^{-5} + .2207}\right)30$$

$$Q = \frac{3759.78}{0.2526}$$

Q = 14879.78 mm3/min

Q = 248 mm3/sec

Required Power

The power required symbolizes the speed with which a job is carried out. This is an approximation to the power we need to add to the extruder so it can melt the plastic. It can be calculated using the following energy balance:

$$P = \rho * Q * C * (T_m - T_0)$$

Where

Density: ρ = 1.07 * 10-6 kg/mm3

Flow rate: Q = 248 mm3/sec

Heat capacity of the material: C = 1300 J/kg K

Outlet temperature: Tm = 200^0C

Inlet temperature: T0 = 20^0C

P = 62.09 W

Hopper Calculations

Stresses in Hoppers

Density: ρ = 1070 kg/m3

Wall friction angle varies from 15 to 30 degrees for carbon stainless steel. So we have taken 20 degree
φ = 20
φ= Angle of wall friction
The coefficient of wall friction is
μ = tan (20) = 0.3639

Compressive Normal Stresses
$pv=\frac{\rho g D}{4\mu K g_c}\left(1-\exp\left(-\frac{4z\mu K}{D}\right)\right)$

gc = gravity constant conversion factor = 1 Kg m/N s2
K = the Janssen Coefficient = 0.4
The hopper which we have designed has a square of 80mm.
So the equivalent diameter will be .
$\frac{\pi}{4}$* D2 = a2
D = 91mm = .091 m
$pv=\frac{1070*9.8*0.091}{4*.3639*.4*1}\left(1-\exp\left(-\frac{4*.1*.3639*.4}{.091}\right)\right)$
pv = 774.56 N/m2

To estimate the normal stress on the wall we apply Janssen's assumption
Pw = KPv
Pw = .4 * 774.56
Pw = 309.825 N/m2

Hopper volume calculations
To calculate the volume, we have approached the inner cavity of the hopper dividing it into two zones, one cubical and one conical. So that the total volume will be the sum of these two areas

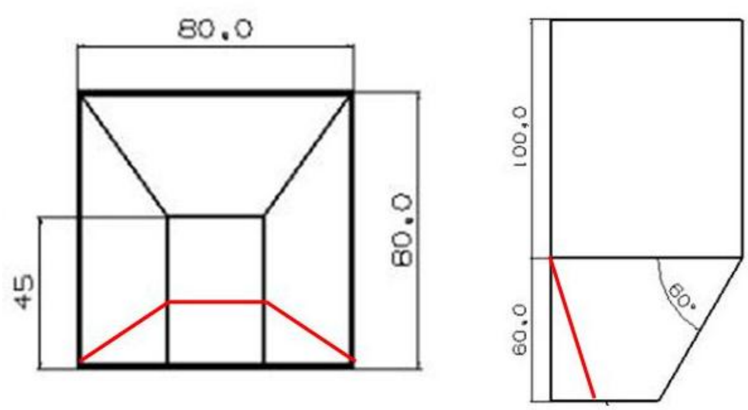

Figure 4 Hopper diagram (Red lines to show Hopper lower part division for volume calculation)

Volume of the rectangular section
V = L*B *H
V =100* 80 *80
V= 640000 mm3
Volume of the trapezoid

Volume of trapezoid = $\frac{1}{3}$ *(A1+A2+√A1*A2)*h
Volume of trapezium = $\frac{1}{3}$ *(900+6400+√900*6400)*60
Volume of trapezium = $\frac{1}{3}$ *9700*60
Volume of the trapezium = 194000 mm3
As the hopper is flat from one side so the volume from the front side excluding the trapezium
So the volume of triangular section is
V = (.5* 15*30*60)
V = 13500 mm3
So the total volume of the hopper is
V =(640000 + 194000 +13500) mm3
V =847500 mm3
Considering that the flow rate of the extruder is Q = 248 mm3/sec. We can calculate the time, in hours, that the extruder can be working without being refilled.

$$T = \frac{V}{Q*3600}$$

$$T = \frac{847500}{248*3600}$$

T = 0.95 hours

So the hopper needs to be refilled after every 0.95 hours so as to the extruder works continuously.

Calculation of b_{min} for Free Flowing Bulk Solid

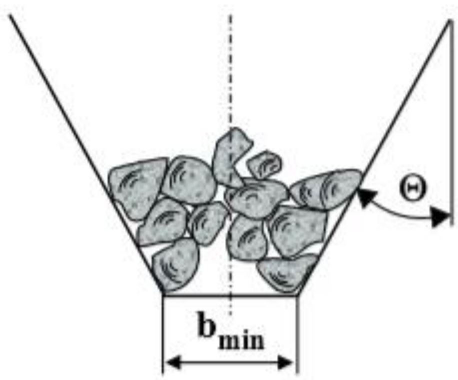

Figure 5 Hopper design for free flowing Bulk solid

The slot of the hopper is rectangular so
$b_{min} = 5\ d0\sqrt{3}$
where
d0 = upper particle size = 3mm
$b_{min} = 5 * 3*\sqrt{3}$
b_{min} = 25.98 mm

In our design we have taken b_{min}= 30 for hopper to free flow of bulk solid.

Heating calculations

Melting Power needed

I have already chosen our resistances, ensuring that allow us to obtain the required temperature of 200ºC, as they can reach 250ºC. However, we think is also good to have an approximation of the power that they will need.

$W = \rho * V * C * \Delta T$

Density: ρ = 1.07 * 10-6 kg/mm3
Heat capacity of the material: C = 1300 J/kg K

To calculate the volume enclosed inside the extruder we depreciate the volume occupied by the screw helix. In this way, the volume of plastic will be the difference between the volume of the chamber inside the cylinder and the volume occupied by the screw.

The volume of barrel cylinder is:
$V = \pi * l * r^2$
Where
Length = l =300mm
Radius = 12.5mm
V = 147262.15mm3
W = 36871.5 J

Working and Results
The main part of the extruder is a barrel containing a screw (also sometimes referred to as an "auger") which is connected to a heater toward its far end. On the other end, the screw is connected to an electric motor which will via mechanical action, transport the resin pellets through barrel towards the heater. Pellets are gravity fed continuously from a hopper. As the motor is continuously driving the auger, the resin pellets are pushed into the heater. The ABS pallets will get soften and melt because of the heat from heating band that is evenly distributed by using asbestos ribbon and are then pushed mechanically through a die. Pushing the soft ABS through the die will cause it to form a continuous filament strand with the diameter of die. Screw is used to control the flow and strainer is used to smoothen the flow. Air fan cool down mechanism is used to cool down the filament after coming from the die. The filament will be stretched out of die till the end wheel and it will be rolled using 12 V DC motor.

Extruder parts CAD and Real parts images

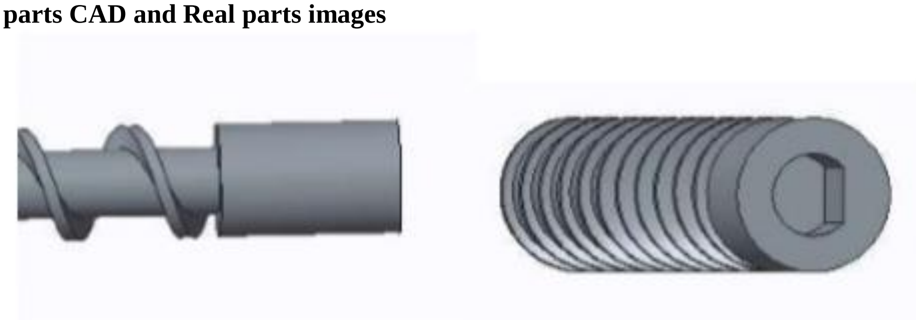

Image1 Screw CAD Model

Image2 Screw

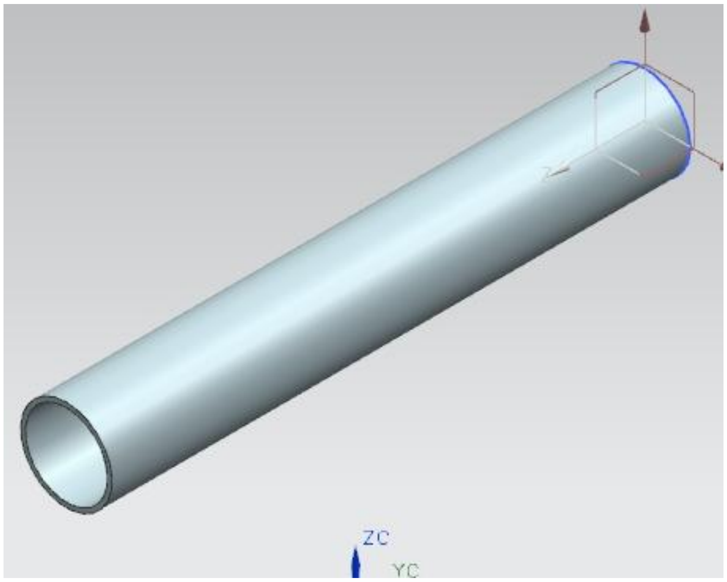

Image 3 Cylinder CAD Model

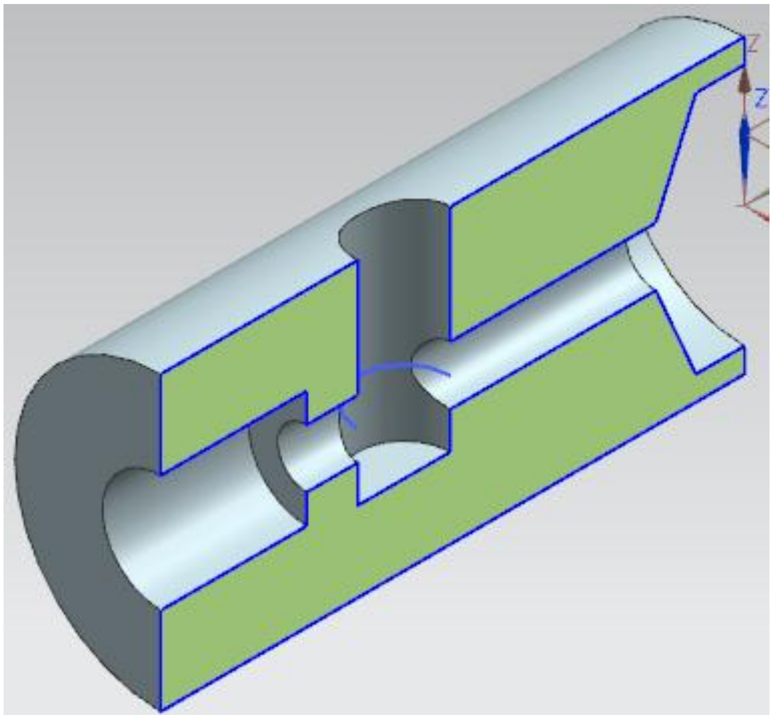

Image 4 Barrel extension CAD Model

Image 5 Barrel Extension with Screw

Image 5 Barrel Extension with Strainer

Image 7 Hopper

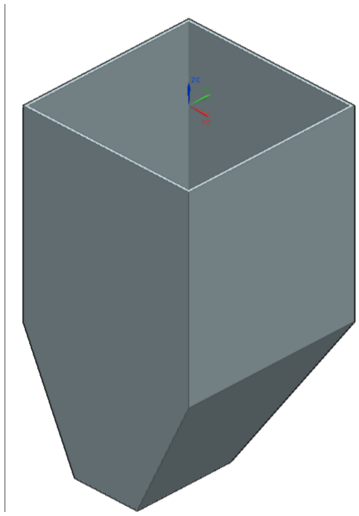

Image 8 Hopper CAD model

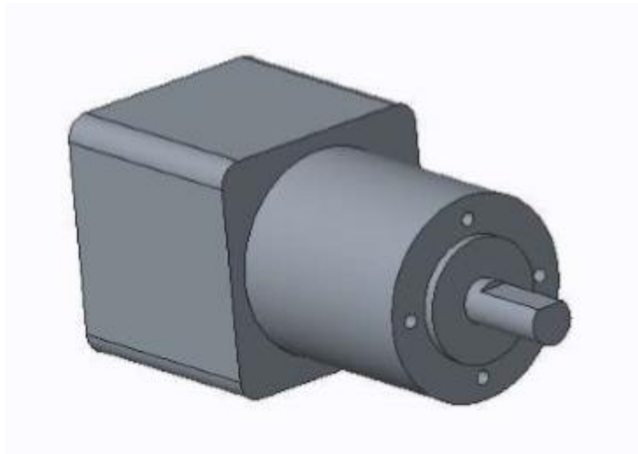

Image 9 Motor CAD Model

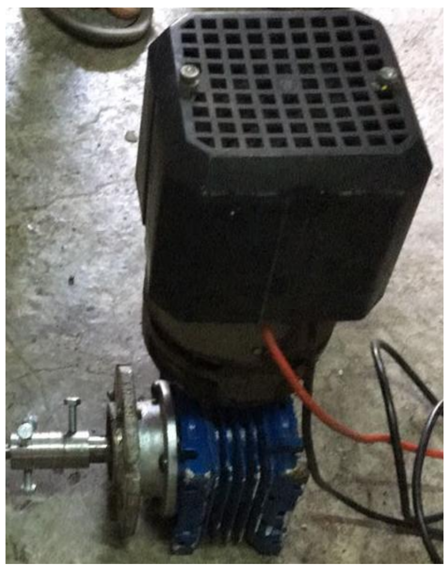

Image 10 600W Worm Geared Motor

Image 11 24 V 30 Amp DC SMPC

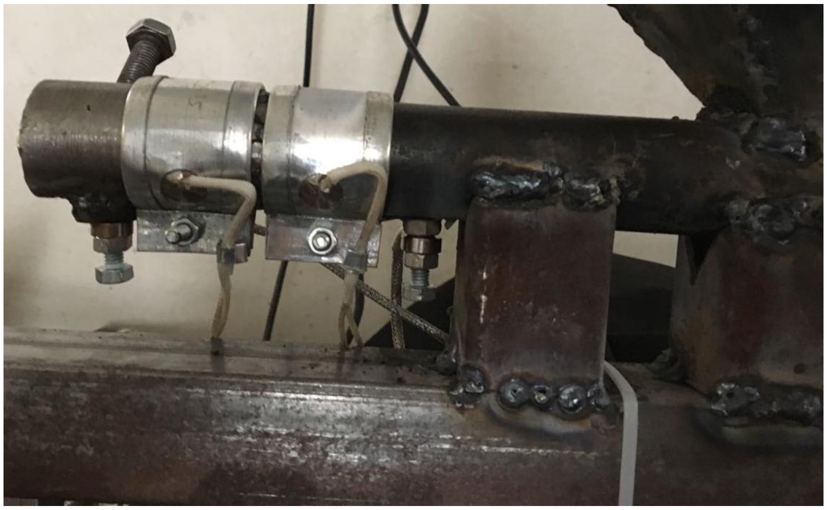

Image 12 Heating Bands

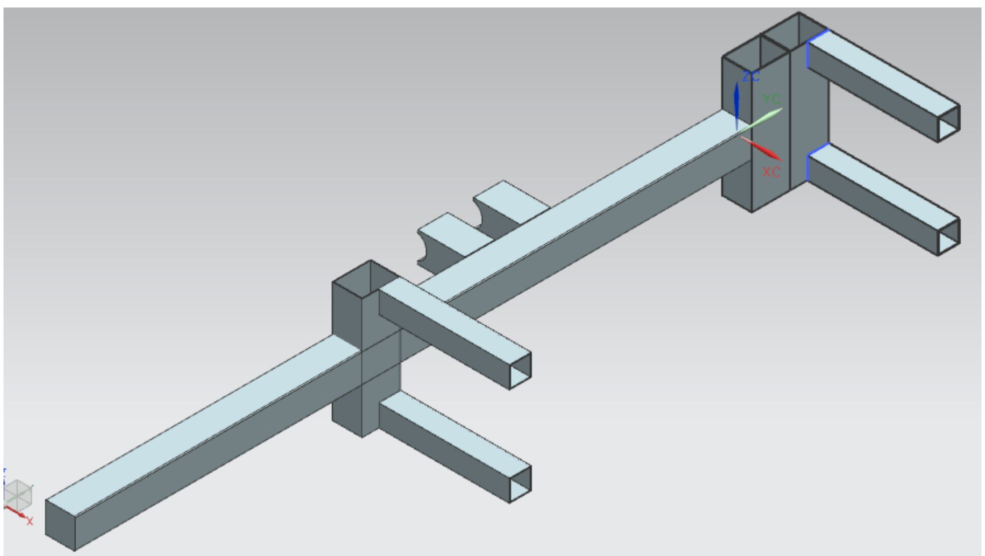

Image 13 Fixing system CAD Model

Image 14 Fixing system

Image 15 ABS Filament Extruder

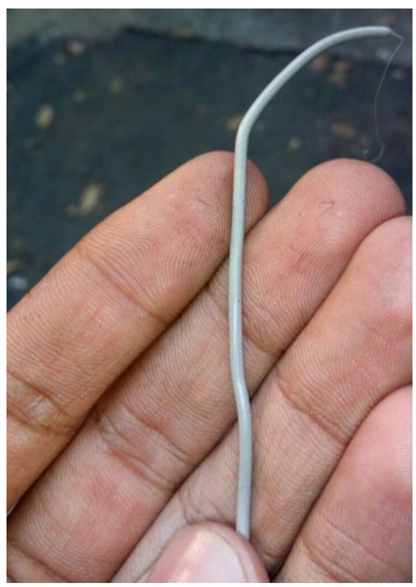

Image 16 ABS Filament Extruder Output

Conclusion

The developments in 3D printing have led to the production of objects made from materials such as plastic, metal, paper and even food. This has given end users the opportunity to explore their creativity. 3D printing is being used by universities, manufacturing companies, and everyday users as a quick method of prototyping designs, exploring the capabilities of this technology and seeking ways to improve it. Because of the quick emergence of this technology, leaps have been made towards improving manufacturing.

The development of screw extrusion will hopefully open doors to new ideas for 3d printing. Screw extrusion will allow users to have access to a wider variety of materials with a high resolution for their 3d printed parts.

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