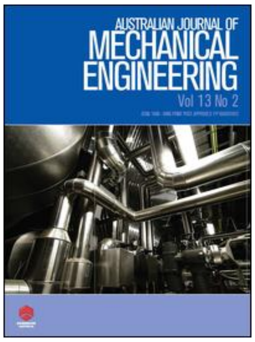

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A novel design to external filament extruder for 3D printer

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ABSTRACT

This paper presents a novel design to use polymer grains of Acrylonitrile Butadiene Styrene (ABS) as a filament for a 3D printer. In the suggested design special extruder for ABS polymer grains were designed. This novel design may comprise an important step towards the improvement of using 3d printers in large scale manufacturing.

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Design; filament extruder; design; 3D printer

1. Introduction

3D printing refers to the operation that creates three-dimensional objects by joining or solidifying material under automatic control (Cummins 2010). An object from the 3d printer can be in any geometry or shape according to digital data from the automatic control unit. Electronic data in control unit composes from an Additive Manufacturing File (AMF), these data describe the extruder path to add the filament layer by layer (Mohammad Taufik Prashant Kumar Jain 2013) to produce the required object. Feedstock material in the 3D printer is thermoplastic called filament (Clive Maier 1998). There are different types available for filament classified according to mechanical properties, fused temperature, and diameter. Today, most common types of 3D filaments are Acrylonitrile Butadiene Styrene (ABS) and Polylactic Acid (PLA). ABS filament has excellent impact resistance, strength, and flexibility. The melting temperature of ABS is high (210–250°C). PLA filament has a smooth and sheen appearance. The melting temperature of PLA is low (180–230°C)(C.A. 1975). One of the main key parts in the 3d printer is the Extruder, in the ordinary 3d printer there are two types for extruders; Direct and Bowden extruder. Indirect extruder, the filament is fed directly to the Hot End from the spindle (Figure 1). In Bowden extruder the filament is feed from a distance to the hot end (Figure 2) Table 1 comprise between main functions in Direct and Bowden Extruder (Bégin-Drolet et al. 2017; Yampolskiy et al. 2016; Jassmi1, Najjar, and Mourad 2018).

Additive manufacturing can be classified into three categories according to its technologies: selective laser sintering (SLS); Fused deposition modeling (FDM); Stereo Lithography (SLA) and digital light projection (DLP). In SLS Technology the laser is used to melt powdered material to perform the first layer then another powder layer is added to perform the second layer and so on to finish the required 3D object (Herrmann et al. 2014). FDM Technology uses a computer program to convert the CAD model into layers for constructing the object layer-by-layer by heating and extruding the filament (Bickelhaupt F Solà M Guerra C Baerends E Ravenek W 2007). In SLA 3D printer UV-laser beam or a digital light projection (DLP) to solidify resin to produce the desired 3D object (M 2016).

Nowadays 3D printer has experienced rapid development on the material used as a raw material and in printing technique. The 3D printer can produce products by using powder materials such as cement, sand, plaster, ceramic and metal (Ben Utela, Duane Storti, Rhonda Anderson 2008; R. Singh 2009). Although limited research on using polymer for 3D printers has been conducted, little research about using powder polymer is available (Giordano RA1, Wu BM, Borland SW, Cima LG, Sachs EM 1996; Ahn SH, Montero M, Odell D, Roundy S 2002). This paper describes the design of a 3D printer intended specifically to use polymer grains of Acrylonitrile butadiene styrene (ABS) as a raw material in the additive manufacturing process. The main idea in the design is making the extruder head have the ability to convert ABS granulates to the 3D object. Figure 3 shows a description of the techniques used in the investigation.

2. Parts design

The main components commonly used in 3d printer design are power screw, nozzle, linear and radial bearing, roller and coupling. In the current section, we will discuss the design for unstandardized parts.

2.1. Screw design

It is used to push the molten material towards the end nozzle, according to the screw size the flow rate and the spinning speed of the printer can be determinate. Figure 4 shows the main parameters in the extruder screw.

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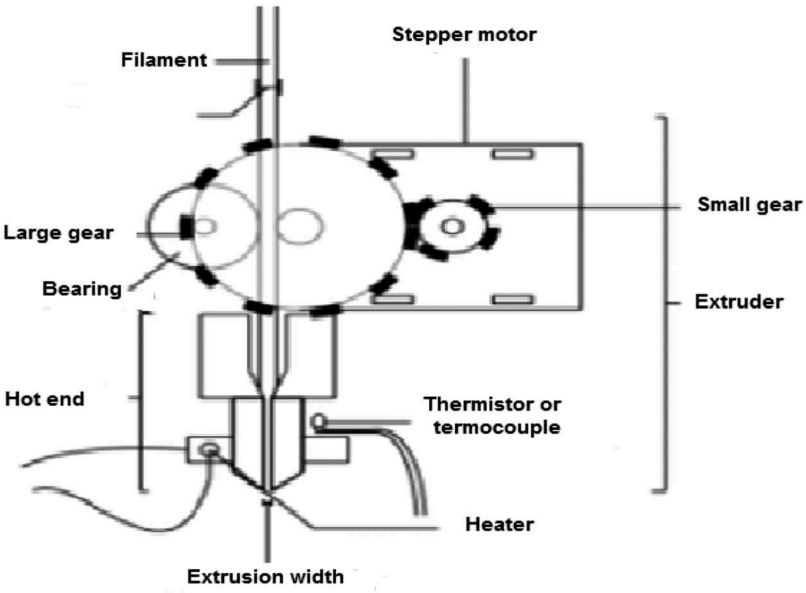

Figure 1. direct extruder mechanism.

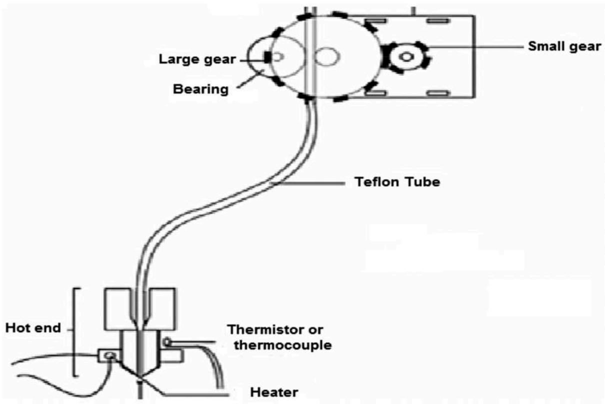

Figure 2. Bowden extruder mechanism.

Table 1. comparison between functions in direct and Bowden extruder.

Function	Direct Extruder	Bowden Extruder
The weight of moving part	Heavyweight	Lightweight
printing times	slow	Fast
accuracy	High	Low
Handles flex	High	Low

The diameter we decide to work with is 30 mm, in order to reduce the weight of the screw the relation between the length and the diameter (L/D) is 5/1. One channel was needed to very small flow so, m = 1. The helix angle of the screw depends on the gap between the pitch (t), so t = D. Helix angle (θ) can be calculated from the following Equation (1) ("Mechanical Engineering Design nd),(Ralph S. Shoberg 2010):

$$\theta = tan^{-1}\frac{t}{\pi.D} = \ 17.66^{0} \tag{1}$$

The ridge width (e) is calculated by multiplication the diameter with 0.12,

So, e = 3.6 mm.

Screw length is the total of feeding, compression, and metering zone. Feeding zone is about 20% of the screw length, compression zone is about 32% and the metering zone is about 38%. While the length is equal 150mm the length of each zone will be:

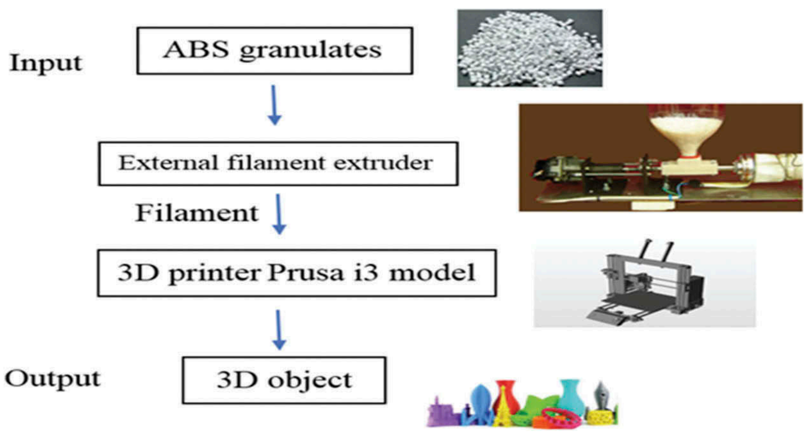

Figure 3. Investigation techniques.

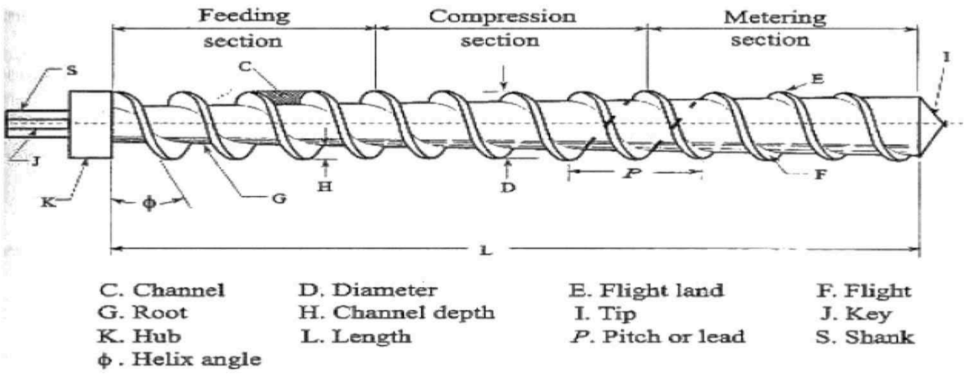

Figure 4. Main parameters in the extruder screw.

Feeding zone: L1 = 0.25 * 150 = 37.5 mm
Compression zone: L2 = 0.32 * 150 = 48 mm
Metering zone: L3 = 0.43 * 150 = 64.5 mm

The clearances or the space between cylinder and screw (h1) is calculated from the following Equation (2)

$$h_1 = D * 0.2 = 6 \text{ mm}. \tag{2}$$

The filet clearance (h2) or the space between thread and cylinder interior surface is calculated from Equation (3).

$$\delta = D * 0.002 = 0.06 \tag{3}$$

Compression ratio (Z) is the channel depth at the screw end and it usually takes a value between 4–2 in the current design Z is = 3. So, final clearance h_2 calculated from equation (4). Table 2 summarized the results of all screw parameters.

$$Z = \frac{h1}{h2} = 3 \qquad h_2 = \frac{h1}{Z} = 2 \text{ mm}.$$

Initial root radio (r) is obtained from the following:

$$r = \frac{D}{2} - h1 = \frac{30}{2} - 6 = 9 \text{ mm} \tag{5}$$

End root radio (R) is obtained from the following:

$$R = \frac{D}{2} - h2 = \frac{30}{2} - 2 = 13 \text{ mm} \tag{6}$$

Table 2. values of all screw parameters.

parameters	value
Diameter D	30 mm
Pitch t	31 mm
helix angleθ	17.66
length of feed zone L1	37.5 mm
length of compression zone L2	48 mm
length of metering zone L3	64.5 mm
initial clearance h1	6 mm
clearance of the filet δ	0.06
final clearance h2	2 mm
Initial root radio r	9 mm
End root radio R	13 mm
ridge width e	3.6 mm
Number of channels m	1

2.2. Nozzle dimensions

The diameter of the outer filament is 0.4mm, so the outer diameter (d_1) of the nozzle will be 0.4 mm. The inner diameter (d_0) of the nozzle can be calculated from the Equation (7):

$$d_0 = D - 2*h_2 = 56 \text{ mm} \tag{7}$$

Figure 5 illustrates the design of the nozzle,

Volumetric flow (Q) calculated from the following Equation (8):

$$\mathbf{Q}^{\cdot} = \left(\frac{\propto *k}{k + \gamma + \beta}\right) * \eta \tag{8}$$

Where

$\propto$: coefficient of drag flow, calculated from Equation (9)

$$\propto = \frac{\pi * D * h2 * m * \left(\frac{t}{m} - e\right) * \cos^2\theta}{2} = 2258 \tag{9}$$

η: *speed* of the spinle = 70 rpm.
β: coefficient of pressure flow, calculated from equation (10)

$$\beta = \frac{\pi * sec\theta * h2^m * \left(\frac{t}{m} - e\right) * \cos\theta}{L * 12} = 0.0921 \text{ mm}^3 \tag{10}$$

γ: coefficient of filtration flow calculated from equation (11)

$$\gamma = \frac{\pi * D^2 * \tan\theta * \delta^3}{L * e * 10} = 0.001978 \text{ mm}^3 \tag{11}$$

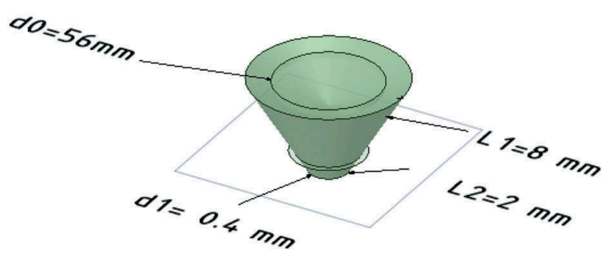

Figure 5. 3D model for the nuzzle.

Figure 4 shows the 3D model for the nuzzle, k constant of head geometrical (for the conical and cylindrical shape)is calculated from Equation (12)

$$k = \frac{1}{\sum \frac{1}{k1} + \sum \frac{1}{k2} + \ldots + \sum \frac{1}{ki}} \quad (12)$$

K1 for the conical shape it is obtained from the following:

$$k1 = \frac{3 * d0^3 * \pi * d1^3}{(d1^2 + d0^2 + (d0 * d1)) * L1 * 128} = 0.03273 \quad (13)$$

K2 for the cylindrical shape it is obtained from the following:

$$k2 = \frac{\pi * d1^4}{128 * L2} = 0.0003142 \quad (14)$$

So, k = 0.000311

From the previous calculation, we can obtain the value of the flow rate ($\mathbf{Q}^{\cdot}$) = 6.5mm^3/sec

The required power (N) for the extruder to melt the plastic determined from the equation energy of balance (14)

$$\mathrm{N} = \rho * \mathrm{C} * \mathrm{Q}*(\mathrm{T_m}+\mathrm{T_0}) \quad (15)$$

Where the thermal and physical properties of selected material (ABS) are:

Density (ρ) = 1, 03*10^{-6} Kg/mm^3

Heat capacity C = 1.47 KJ/Kg°C

Outlet temperature: Tm =105°C.

Inlet temperature: T0 =25°C.

So, required power (N) = 0.196833 Mw

2.3. Cylinder design

The screw is rotating inside a metal cylinder, so the inner diameter of the cylinder will be the total of screw diameter (D =30) and the clearance (0.07mm). The required length for the cylinder to cover the screw is 144mm.

2.4. Feeding system and hopper design

Figure 6 shows the dimension and geometry of the hopper; the hopper is located on top. As Figure 6 illustrate the hopper consists of two geometries (conical and cylindrical), so the volume of the hopper will get from the equation (16):

$$\mathrm{V_H} = \mathrm{V}_{\text{conical}} + \mathrm{V}_{\text{cylinder}}$$

$$\mathrm{V_{conical}} = 0.33{*}\pi{*}\left(\frac{D}{2}\right)^2 * h = 125898.3\ \mathrm{mm}^3. \quad (17)$$

$$\mathrm{V_{cylinder}} = \pi{*}\left(\frac{D}{2}\right)^2 * h = 381510\ \mathrm{mm}^3. \quad (18)$$

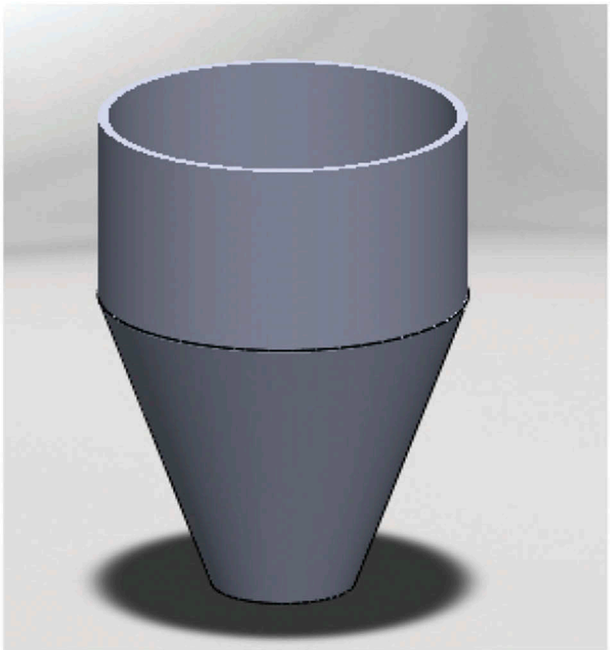

Figure 6. 3D model for the hopper.

Where D = 90, h = 60, So from equation (16) the volume of hopper (V) is =507, 408.3 mm^3.

According to the calculated flow rate ($\mathbf{Q}^{\cdot}$) these hopper can work to time 21.7 hours without needing to refill.

$$\mathrm{T} = \frac{V}{Q * 60 * 60} 21.7\mathrm{hr}. \quad (19)$$

3. Material selection

In order to produce parts have high corrosion resistant Steel 304 with a composition of (Fe 08, C 17.5, Cr 20, Ni 11, Mn 2, Si 1, P0 45, S 03) was selected to make the screw. Figure 4 shows the prediction of temperature distribution during the extruded process, the model was made using the program (FEHT 4). The program developed by the University of Wisconsin – Madison. In the simulation process, 540 nodes were used with 970 triangular elements. Inlet temperature is set at 25 c, the cylinder temperature is set at 105 C and screw temperature is set at 50 c, the program ignore convection .thermal conductivity of the steel 304 is taken as 14 W/m.K. the prediction model confirm that thermal conductivity of the selected material (steel 304) can lead to high temperature during extruded process(Paul Gramann 1998). The program validated by measuring the actual temperature at three locations: at the inlet; at the middle of the extruder and at extruder outlet. In order to measure the temperature laser surface thermometer (Maverick LT-02) was used. Aluminum sheet with thickness 2 mm was used to make the cylinder, Brass was used to making the Nozzle. The connection joint between hopper and extruder was made from Teflon since it is an excellent insulator and has a high melting temperature (260 C). Hopper made with a material easy to manufacture, light in weight and resistant to temperature, so it is fabricated in Polypropylene. Figure 7 illustrates temperature distribution during extruded for the selected material.

4. Motor selection

In order to produce a simple, lightweight and a cheap 3d printer, stepper motor NEMA 17 was selected. Table 3 shows the full specification.

5. Heating system design

Three electrical (40 watts) heaters work with 12V are used to reach a temperature over 150 C. the heaters are attached to the aluminum cylinder as shown in Figure 8.

The heating process made in three stages first stage used in feeding zone to elevate the ABS to 50, second stage used in compression zone to elevate ABS the 90 and last stage used in metering zone to elevate the ABS to 110 C. Thermocouples (Pt 100 type) are attached at each heater to control in the temperature.

6. Description of the existing 3D printer

Figure 9 shows the existing 3D printer used in the investigation. The printer design made according to Prusa i3 model, which is the most used printer in the world. The head can move in the X and Y axes and the base can move in the Z axes. Four stepper motors were used to control in the X, Y, and Z axis and to control in the extruder. The printer uses The Marlin Firmware to run, it converts files to G-code command. This Firmware is work with Arduino board. The track of x-axis is 900 mm and track of y-axis is 1000 mm. The output filament from the external extruder (Figure 10) will feed the printer extruder head to produce the required object.

Table 3. data sheet of stepper motor NEMA 17.

Step Angle	1.8°
Voltage	12V
No of phases	2
torque of	4.2 KG.cm
Rated Current	1.3A/Phase

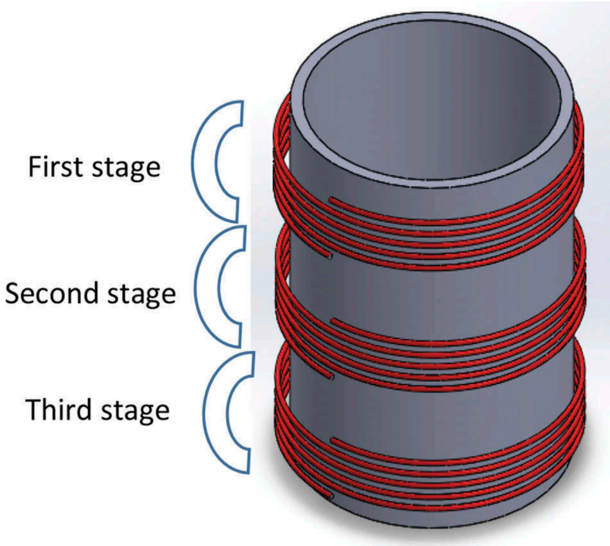

Figure 8. 3D model for the heating system.

7. Results and discussion

In order to find the suitable conditions to obtain accurate 3D object different tests were made. The distance between the extruder nozzle and 3D printer head (X) and the rate of feed (F) in the designed external filament extruder have a significant impact on the printing operation (Bégin-Drolet et al. 2017). Table 4 shows the conditions of the experiments, the criteria of evaluation will be depending on the successful in feeding the 3D printer head with the filament to 1 hour without stopping.

Figure 11 shows the working time at all experiments, it can be seen from the plot that the working time increases up to the selected time for the test (60 min) by the increase in distance between the

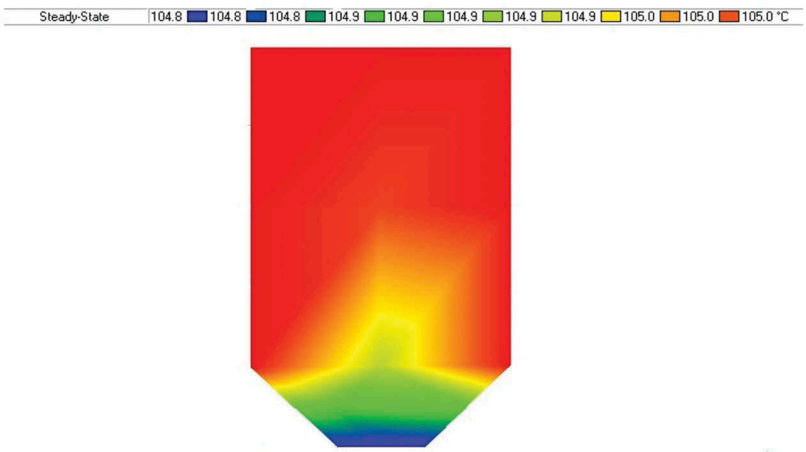

Figure 7. Temperature distribution during extruded for the steel 304.

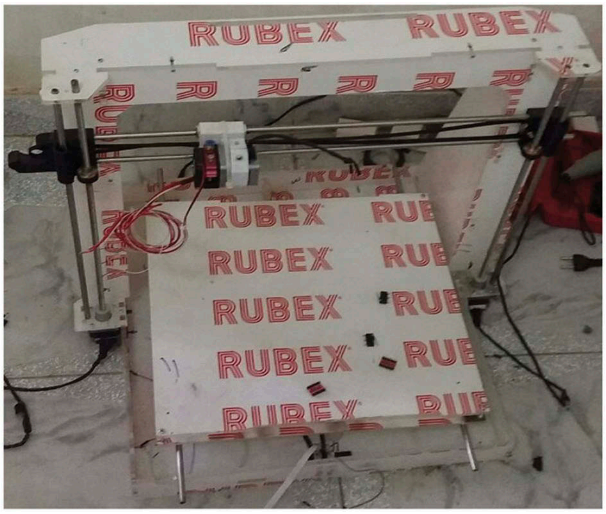

Figure 9. Overview of the existing 3D printer.

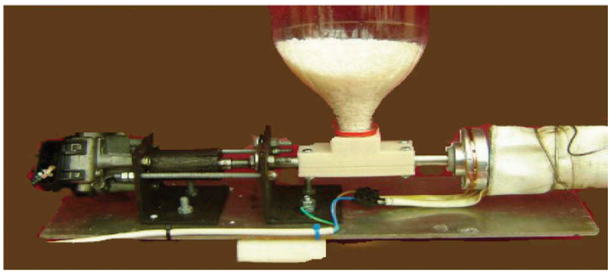

Figure 10. Overview of the external filament extruder.

Table 4. experiments conditions.

Experiment no.	X (mm)	F (mm/min)
1	3000	20
2	3500	40
3	4000	60
4	3000	40
5	3500	20
6	4000	20
7	3000	60
8	3500	60
9	4000	40

extruder nozzle and 3D printer head and by decreasing in the rate of feed in the designed filament extruder. This is because when the distance between the extruder nozzle and 3D printer head increase the filament can find the required time to cool and produce a hard layer on the outer surface, also when the rate of feed is decreased the diameter of the filament increases significantly according to André et al (Bégin-Drolet et al. 2017).

After we find the suitable distance between the extruder output and 3D printer head and the suitable rate for feeding, we test the suitable temperature for the 3D printer extruder head (90, 95 and 100°C), Figure 12 shows the output object at each temperature. In order to study the quality of the finale surface digital microscope was used to magnify the outer layer (figure 13) for the output objects at each temperature. It is clearly seen from the figures that the best surface finish and accurate object shape were obtained at a high temperature (100°C). This increase in the quality possibly resulted from full melting for the filament during the extruding process(LIM, S., BUSWELL, R.A., LE, T.T, AUSTIN, S.A., GIBB and THORPE 2012)(Daniel Weger, Dirk Lowke 2016).

8. Conclusion

A new external 3D printer extruder was successfully produced and tested for the production of 3D ABS object. The suitable conditions to use the external extruder were found at distance equal 4000 mm, also the suitable feed rate for extruder is equal to 20 mm/min. the output filament produced by the designed extruder can produce high-quality object when it formed at high temperature (100°C). The new technique can produce an object with excellent precision and surface finish. The suggested design can be open the door for using 3D printer technique in the large scale manufacturing.

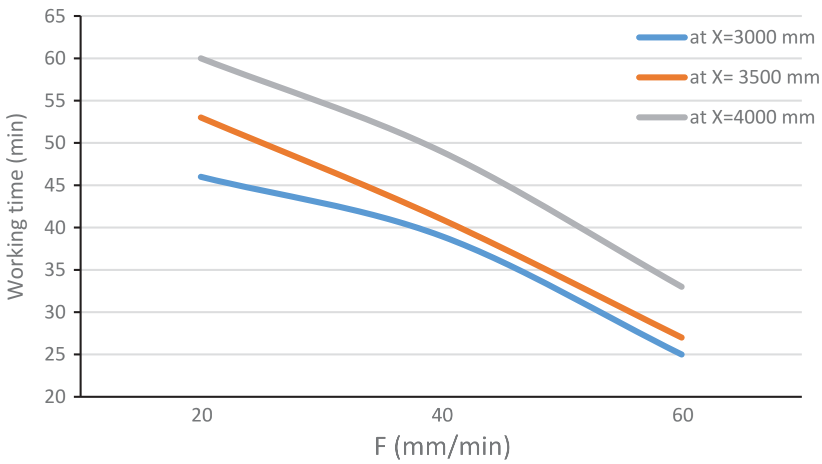

Figure 11. Working time at each condition.

Figure 12. Output objects at different temperatures.

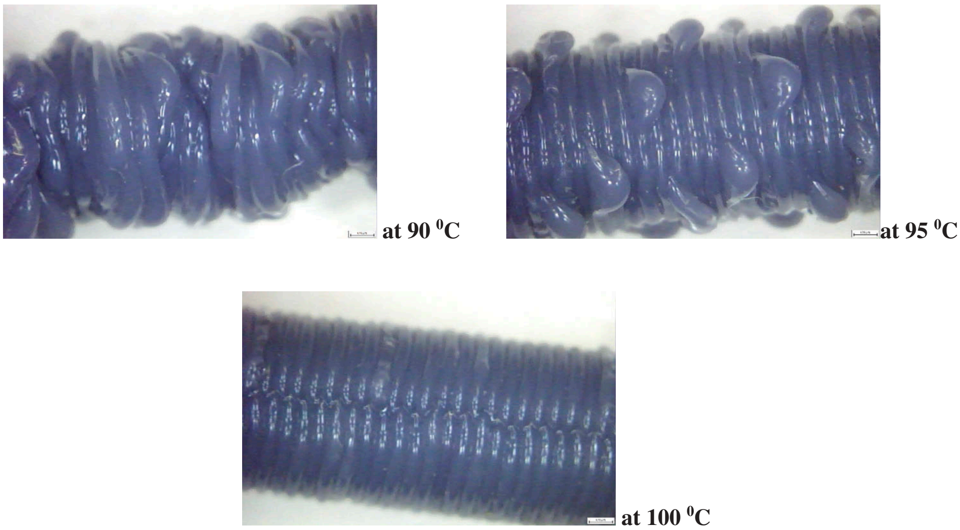

Figure 13. Surface magnification for the output objects.

Disclosure statement

No potential conflict of interest was reported by the authors.

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