Design and development of solid particle ejector for an FDM 3D printer

Kok Siang Lee[1], Tze Chuen Yap[2]

[1]Fusionex International, Section 13, 46200 Petaling Jaya, Selangor, Malaysia
[1]School of Engineering and Physical Sciences, Heriot-Watt University, Edinburgh, Scotland
[2]School of Engineering and Physical Sciences, Heriot-Watt University Malaysia, Putrajaya, Malaysia
[2]t.yap@hw.ac.uk

Abstract

Fused deposition modelling (FDM) printed polymeric parts are weaker compared to injection moulded counterparts. Reinforcing polymers with additional materials during 3D printing is one of the possible methods to improve the mechanical properties of FDM printed polymers. In this study, an innovative ejector for short fibres was developed that can be connected to existing FDM 3D printers. The additional ejector is capable of depositing short fibres during printing to produce short fibre reinforced thermoplastic (SFRT) composites. The main advantage of this ejector is that it can be mounted on the commercial FDM 3D printers and the existing thermoplastic extruder does not need to be modified. A prototype of the ejector was built and tested. The fibre deposition rate of the ejector was tested and compared to the designed specifications. The results of prototype testing show that the fibre deposition rate is consistent with the designed value. Along the way, there are some challenges such as ejector reliability and deposition rate. These challenges will be discussed in detail.

Keywords: Short fibre reinforced composite; additive manufacturing; in situ reinforcement

1. Introduction

Additive manufacturing (AM) is currently used in the manufacturing industry for its flexibility in producing 3D products. Fused Deposition Modelling (FDM) is one of the best-known techniques of AM. Notwithstanding the widespread use of FDM 3D printers in various fields, it has weaker mechanical strength compared to the traditional injection moulding process. Like injection moulding, it is a one-piece job, while FDM parts are made layer by layer. The layer-by-layer manufacturing process creates many voids in the contact area of the filaments [1]. Therefore, the mechanical properties of the part produced with an FDM 3D printer are inferior compared to the mechanical properties of conventionally produced parts. To significantly improve the properties of FDM parts, fibre reinforcement is used [2]. There are two types of FDM 3D printing composites: short-fibre reinforced thermoplastics (SFRT) and continuous-fibre reinforced thermoplastics (CFRT). Most research on SFRT composites is concerned with the development of a new starting filament consisting of micro- or nanocomposite fibres [3]. In contrast, CFRT composites are a combination of fibre reinforcement and thermoplastic matrix. There are three different methods for CFRT [4].

- Embedding Before the Printing: The simplest way of doing as it does not need to have a major change on certain machinery.

- Embedding in the Print Head: (shown in Figure 1).
- Embedding on the Component: Usually comes out with a specific extruder to deposit the fibres (shown in Figure 2).

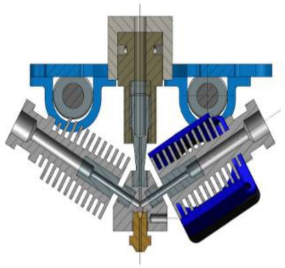

Fig 1: Embedding in the print head [4]

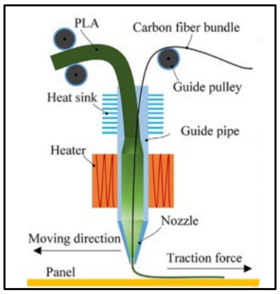

Fig 2: Embedding on the component [5]

Figure 2 shows an existing design concept of CFRT '*embedding on the component*' with a single extruder. The feed wheels act as controllers to ensure uniform deposition of the composite material and plastic filament. The concept is controlled by the feeding system. The main disadvantage of CFRT embedding before printing and CFRT embedding in the print head is that the reinforcement (fibre) is still not able to reinforce the weakest part - the voids between the prints. In addition, the volume fraction of the fibres can only be changed to a limited extent, so the fraction of fibres that reinforce the structure is controlled [5]. In the current market, SFRT is not widely used because of the limited control of fibre placement. Therefore, the main objective of the current work is to design and build a mechanism to apply reinforcement material (fibres or particles) uniformly to the desired 3D printed product during the printing process.

2. Materials selection for CFRT

The filaments used in FDM 3D printing have the same concept as thermoplastics. When the filaments are heated, they melt instead of burning, and solidify as they cool. The selected filaments are inserted into the heating chamber of an FDM 3D printer and extruded from the nozzle to produce the desired design product layer by layer. Most 3D printers are equipped with a single extruder, but there are also some FDM 3D printers with two extruders on the market. Dual extruder 3D printers can print in different colours or with different types of filaments.

2.1 ABS Filament

Acrylonitrile Butadiene Styrene (ABS) is a good printing material for FDM 3D printing. Heated ABS also produce fumes that will irritate users. Hence, a good ventilation is needed while printing with ABS. The print temperature is around 210°C – 250° C.

2.2 PLA Filament

Poly Lactic Acid (PLA) has a diverse variety of uses. PLA can print faster than ABS and heated printer bed is not required. Furthermore, the PLA finished products have a reasonably good strength. It is durable and serve some level of impact resistance. Apart from 3D printing, PLA also will be used in food packaging, recycling tableware etc. The print temperature is around 180°C – 230°C.

2.3 Fibre Glass

Fibreglass is made from synthetic silica sand that is heated to high temperatures and formed into opaque, ultra-fine and fibrous strands. The continuous addition of fibreglass strands to a product can improve the physical properties of the printed product. Therefore, glass fibre is known as a good reinforcing composite material. Compared to a pure ABS printed product, printed parts with glass fibre reinforcement are 20 times stronger and 10 times stiffer in tension than an ABS basic printed part [6]. High strength, high temperature (HSHT) glass fibre is a reinforcement composite material specifically designed for users who need to produce stronger parts that are exposed to higher ambient temperatures above 105°C. For example, automotive applications such as engine components that are exposed to temperatures above 140°C are reinforced with HSHT glass fibre [7]. When 'failure critical' parts are used under cyclic loading conditions, HSHT glass fibre reinforcement can not only provide similar strength to carbon fibre reinforcement without causing structural failure. Alternatively, it will yield plastically under limited rebound energy [6].

2.4 Carbon Fibre

Carbon fibres are made up of organic polymers which undergoing low temperatures. It is also known as mixture of chemical, additive thermal conduction, mechanical treatments and finally crystalline by its nature. The resultant outcome has become the highest strengths to weight ratios compared to steel and titanium. In 3D printing, using of carbon fibre as reinforcement will have 25 times stiffer than basic ABS printed part. With the use of carbon fibre reinforcement, the part will also have a 50% higher strength-to-weight ratio if compared to 6061 aluminium [6].

The two thermoplastics, ABS and PLA, differ significantly in some aspects. ABS has a higher structural integrity and is more suitable for mechanical use because it has a better resistance component. In contrast, PLA offers more reliable printing and better textural performance, as well as greater versatility in printing environments. In this project, PLA was chosen because ABS is strong enough compared to PLA and therefore a significant change in the mechanical properties of the final PLA product can be effectively detected when the nanocomposite is applied to PLA during printing. The general advantages of using PLA are also the following

- PLA is low in cost.
- Biodegradable, material made up of renewable sources
- Lower melting point means heating bed is unnecessary.
- Much easier to work with compared to ABS filament.

3 Concept Designs and Selection

Several concept designs were proposed, and a best concept was selected based on selection criteria.

3.1 Concept Design 1

Concept 1 has a cylindrical tube shape with a control mechanism installed at the near end of the tube, as shown in Figure 3. Layers A and B are used to control the flow of the short fibre/particle during deposition. The green markings C and E are solid extrusions, while D and F are cut extrusions. To stop the flow of the short fibre/particle, marker C in layer A is moved to D to fill the hole and stop the flow process. The open flow of the particle/fibre is exactly the opposite of the closing. The arrows that are positive to gravity indicate the flow of the particle/fibre.

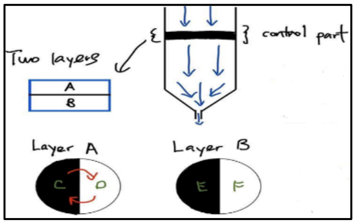

Fig 3 Concept Design 1

3.2 Concept Design 2

This design shows in Figure 4 is straight forward. The blue arrows indicate the flow of particle/fibre. The control part of the design is demonstrated in Figure 4. The red part which is recognised as "piston" is controlling the flow of particle/fibre. The "piston" is operated by a Servo Motor so it can have motion at Y-axis.

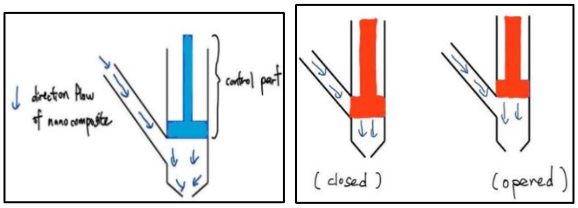

Fig 4 Concept Design 2

3.3 Concept Design 3

The design shown in Figure 5 is very similar to the first conceptual design. The flow of the particle/fibre is positive to gravity and is controlled by a rotating device. The arrows pointing in the direction of gravity indicate the flow of the particle/fibre. The control part of the design is shown in Figure 5. The rotating arrows indicate the direction of rotation of the device. The possible controller for the device is a servo motor.

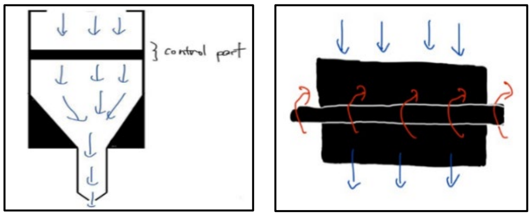

Fig 5 Concept Design 3

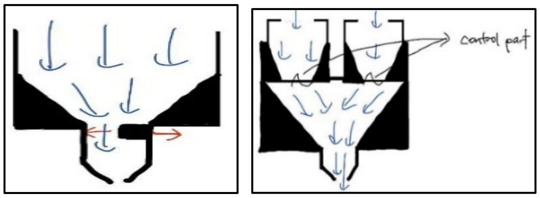

Fig 6 Concept design 4

3.4 Concept Design 4

This design has a double depositional part at the beginning and the flow is gravitationally positive. Figure 6 shows that the reason for the double deposition is to control the flow rate of the particle/fibre and to ensure the consistency of the flow. The arrows in the y-direction indicate the flow direction of the particle/fibre. The control part of the design is shown in Figure 6. The arrows in the x-direction indicate the direction of the control mechanism. When it moves in the right direction, the particle/fibre is allowed to pass and vice versa. The possible controller for the control mechanism is a servo motor. To complete the concept to the first ideas, various technical aspects should be considered. For example, it is important to determine the feasibility of the design, because the result of the design should meet the objective of the task in order to solve the problem. In addition, ease of production should also be considered. The final product may be different from the original design because the complicated structure of the design may lead to ambiguities during the manufacturing process, which will affect the effectiveness of the product. The simplicity of manufacturing and the price of the product are the most important aspects to consider. Apart from effectiveness, these considerations usually serve to meet the customer's requirements. Table 1 shows that the initial idea, design 2, is more important for achieving the project goal as it received the highest score in the decision matrix. Therefore, the final design is selected for the project.

Table 1: Decision matrix for four concept designs

Criteria		Effectiveness	Manufacturing	Ease of use	Cost	Total
Weight		40%	30%	15%	15%	
Design	1	6	5	5	5	5.4
	2	9	9	7	8	8.55
	3	7	9	7	8	7.75
	4	8	5	6	4	6.2

4 Final Design and Assembly

In this section, details of design of the new particle/fibre ejector developed for FDM 3D printing of SFRT composites are explained. According to the SFRT “Embedding on the component” method, particle/fibre such as fibre should be deposited on the melted plastic in a simultaneously manner. In this regard, different conceptual designs were assessed for selecting the appropriate design. As shown in Figure 7, the designed ejector consists of several components like a control feeding system, fibre container and the ejector head.

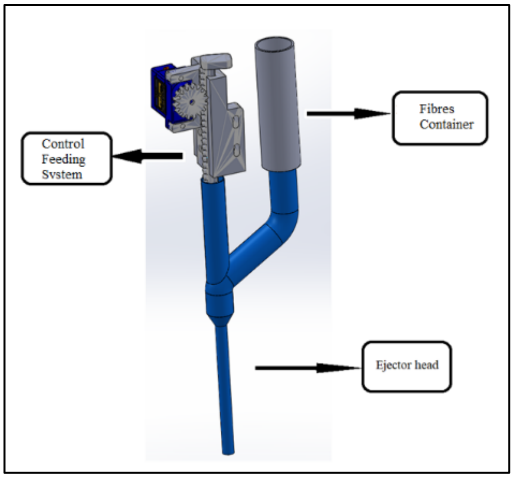

Fig 7: Final assembly of the design

4.1 Ejector Part

As shown in Figure 8, there are two inputs in this ejector design; one for the input (right) of the particle/fibre and the other (left) for the control feed system. Glass fibres with a diameter of 0.001 m flow uniformly through the aforementioned input to be deposited at the ejector head. The movement of the glass fibres is mainly driven by gravity. This design is recommended for the construction of high temperature resistant steel to avoid melting during pressure. Molybdenum steel (Mo) is one of the best choices for fabrication as it has a high melting point of 2623°C. It can be easily alloyed to add additional properties and increase the temperature resistance of other materials.

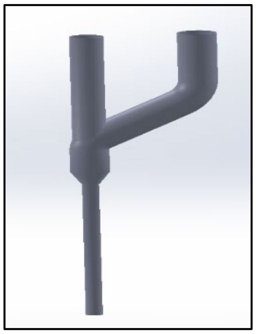

Fig 8 Ejector and its inlets

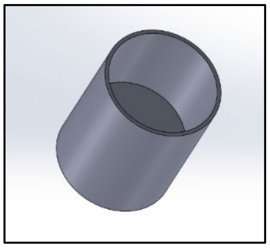

Fig 9 fibre container

4.2 Fibre Container

The fibre container shown in Fig 9 is used to store glass fibres to ensure more glass fibres can be transported throughout the printing process. As for the radius and height of the container is around 0.04 m and 0.1 m respectively, the volume of the container is 0.0005m^3.

The density of glass fibres is $2560 kgm^{-3}$,

$$mass(kg) = Density(kgm^{-3}) \times volume(m^3)$$

$$mass(kg) = 2560 kgm^{-3} \times 0.0005 m^3$$

$$= 1.28 kg \approx 1280 g$$

The container can store around 1.28 kg of glass fibres and is ready to be deposed during the printing process.

4.3 Feeding Control System

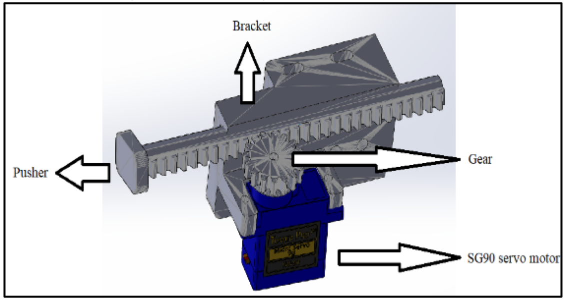

Fig 10 Feeding control system

The feeding control system shown in Figure 10 consists of four components: SG90 servo motor, gearbox, slider and the bracket. The servo motor is connected to a computer control system such as the Uno board to start communication in the system. The gearbox is connected to the servo motor and helps to move the pusher with the rotational force of the servo motor. The pusher, which is 150 mm long, is used to block or release the flow of fibres. The pusher moves in the Y-axis of the final design system. The bracket is designed to hold all the components of the system and provide enough support to absorb all the force coming from the pusher and keep the system in balance.

4.4 Concept Design in the Final System

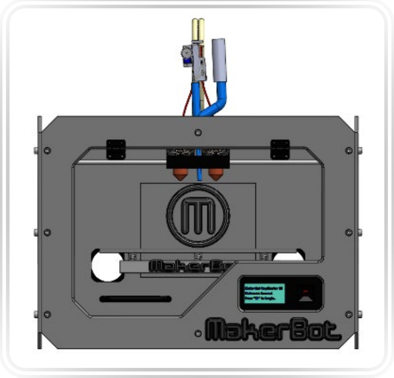

Fig 11 ejector mounted on 3D printer (MakerBot replicator 2x)

The MakerBot Replicator 2x was chosen to implement the particle/fibre ejector. Since the 3D printer has two extruders, the ejector should be placed in the middle of the two extruders to ensure the placement of the fibres on the printed product. The ejector head is placed as shown in Figure 11 and the ejector was held in place with a rubber band to maintain balance during placement.

5 Prototype Testing & Result Analysis

This part gives the details of the prototype set up and all relevant information about the testing of the prototype. The final design of the ejector consists of three main parts as shown in Fig. 12, which are shown in this section: Fibre container, feed control system and ejector head.

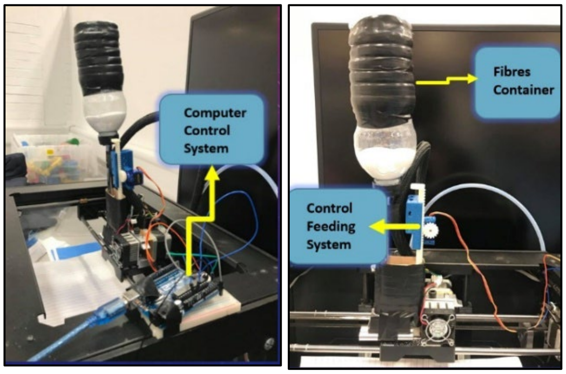

Fig 12 Set up of prototype testing

5.1 Feeding Control System

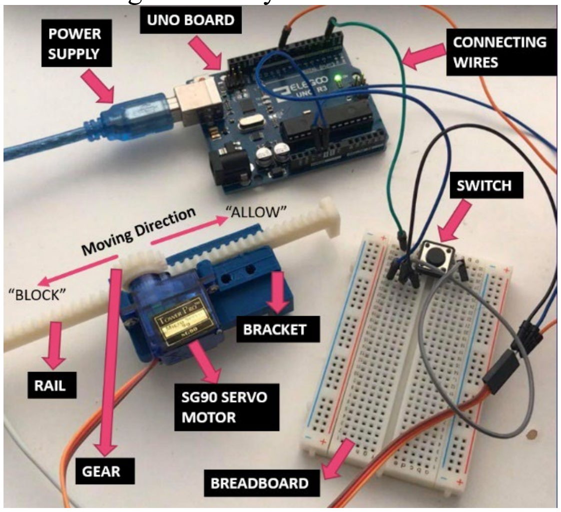

Fig 13 Feeding control sub system

The feed control system is used to control fibre flow throughout the process. In the prototype tests, the components such as the rail, gearbox and bracket are made of acrylonitrile butadiene styrene (ABS) using a 3D printing process. The computer control system consists of a Uno board, a switch, a breadboard and connecting cables. The Uno board is programmed with Arduino and connected to a power supply as shown in Figure 13. When the Uno board is powered, it starts to communicate with the switch and the servo motor. When the switch is pressed, the gear turns 180° counterclockwise to open the flow of fibres. To stop the flow of fibres, the switch is pressed again and the gear rotates 180° clockwise to ensure that the rail stops the fibres from flowing through the system.

5.2 Ejector Head

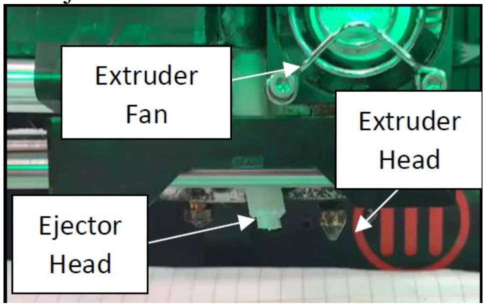

Figure 14 Components of ejector head

The dimension of the ejector head is important as it may impact the flow rate of the fibres and also the accuracy of the fibres placing on the printing product. For prototype, the ejector head is built up of Acrylonitrile Butadiene Styrene (ABS) and covered by heat insulator to prevent melting during printing. Commercial 3D printer has a minimum thickness for the wall of hollow tube to print, hence the diameter of the ejector head can only be minimized to 0.0038 m. As the diameter of the ejector head is proportional to the fibres flowing rate, hence high order technical manufacturing can be acquired to fabricate lower ejector diameter to decrease the fibres flowing rate.

5.3 Fibres Container

In this part, a plastic recycled bottle is used as the fibres container as it has one inlet and one outlet. The volume of the bottle also near to the desired fibres container which has only 0.28kg different. The plastic recycled bottle can store 1kg of fibres glass before deposing.

5.4 Replacement of Glass Fibres

In the prototype testing, the use of glass fibres was replaced by table salt of similar size (0.001

m) and density (2160 kg/m3). The reason of the replacement because of table salt can be easily accessed. Furthermore, the cost of table salt is much cheaper than glass fibres.

5.5 Results of Prototype testing

Prototype testing is conducted to illustrate the functionality of the ejector design. Hence, the glass fibres flow rate is important as it can determine how much fibres placed during the printing process. From the calculated results based on Beverloo's law [8], the ejector design with orifice diameter of 0.0038 m will discharge the table salt at 3.582 kg/hr. To show the relationship between theoretical and prototype, a flow rate experiment was carried out to analyse the data. The average salt deposited weight obtained from the test was 0.0563 kg/min. By conversion, $0.0563kg \times 60\,\text{min} = 3.378kg/hr$. Hence, the prototype has 3.378kg/hr flowing rate.

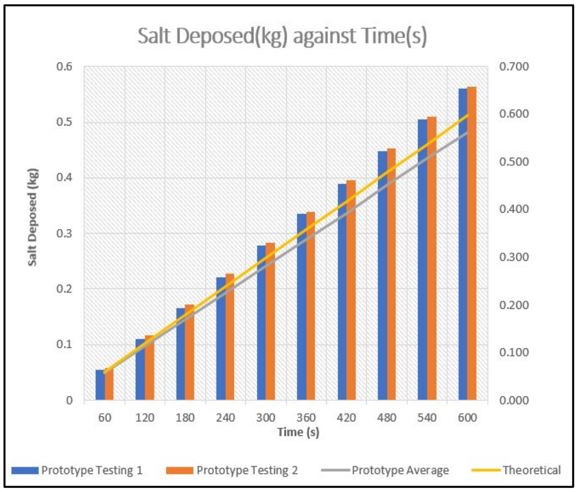

Fig 15: Deposition rate at various time

From the figure 15, the theoretical and prototype salt flow rates were plotted. The result showed that the errors increased depends on time. The ejector deposed lesser salt when the time increases. This may be due to the size of salt may not be consistent as 0.001 mm, some of them might be larger or smaller. Besides, error might occur at the dead flowing spot (as shown in figure 16) of the ejector and salt container causing the salt to be accumulated and create blockage along the time being.

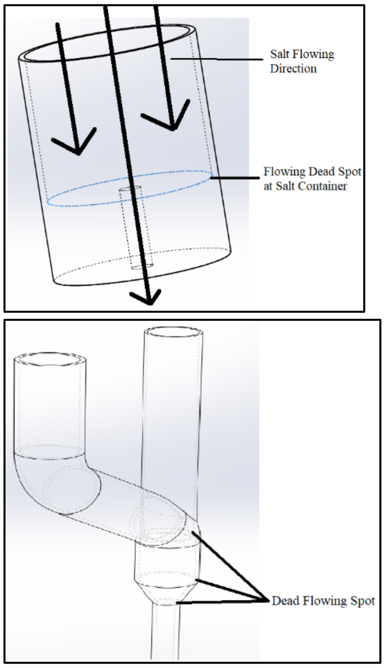

Fig 16 Dead spot found inside (a) container, (b) bend

Hence, some improvement can be implemented to increase the efficiency of the ejector. However, the percentage of error of this experiment is 5.7% which is low and can be negligible. As a conclusion, the prototype design has the flow rate close to the theoretical value. This means that the ejector concept design is able to depose particle/fibre material with manageable flow rate however certain improvement can be advised.

6 Conclusion

FDM parts are manufactured layer by layer. The layer-by-layer production results in a large number of voids in the contact area of the filaments, so the printed product has poorer mechanical properties compared to a product produced by injection moulding. Therefore, an ejector was developed, manufactured and installed on a conventional FDM 3D printer to produce short-fibre reinforced PLA composites (SFRT-PLA). The ejector works by the method of "embedding in the part" and simultaneously deposits the short-fibre reinforcement on the thermoplastic matrix. Some experimental tests are carried out to determine the essential parameters that work in the ejector. Processing parameters such as the dimensions of the ejector head influence the rate of deposition of the fibres. The experimental results show that the deposition rate is 3.378 kg/hr, which is 5.7% lower than the theoretical value. The error is caused by the fact that the deposition particles do not have a uniform size. In addition, the dead spot on the prototype delays the deposition rate because the accumulation of particles can cause a blockage that slows down the whole system. As a result, the particle/fibre ejector has high performance in depositing fibres on the printed product and achieves uniform deposition on the FDM 3D printer, although some improvements should be considered. The ejector can be developed for any FDM 3D printer. The dimensions of the ejector depend on the size of the printer, but the nature of the design remains the same.

References

[1] L. Blok, M. L. Longana, H. Yu and B. K. Woods, “An investigation into 3D printing of fibre reinforced thermoplastic composites,” Additive Manufacturing, vol. 22, pp. 176-186, 2018.

[2] G. Ozkoc, “Short glass fiber reinforced ABS and ABS/PA6 composites: Processing and characterization,” Polymer Composites, vol. 26, pp. 745-755, 2005.

[3] P. Parandoush and L. Dong, “A review on additive manufacturing of polymer-fiber composites,” Composite Structures, vol. 182, pp. 36-53, 2017.

[4] H. Prüß and T. Vietor, “Design for Fiber-Reinforced Additive Manufacturing,” Mechanical Design, vol. 137, no. 11, p. 111409, 2015.

[5] M.Heidari-Rarani, M. R. Afarani and A. M. Zahedi, “Mechanical characterization of FDM 3D printing of continuous carbon fiber reinforced PLA composites,” Composites Part B: Engineering, vol. 175, p. 107147, 2019.

[6] J. Drew, “Fiberglass vs Carbon Fiber,” Markforged, 10 04 2019. [Online]. Available: https://markforged.com/blog/fiberglass-vs-carbon-fiber/.

[7] “High-Strength, High-Temperature Fiberglass,” Markforged, [Online]. Available: https://support.markforged.com/hc/en-us/articles/211358483-High-Strength-High-Temperature-Fiberglass.

[8] C. Mankoc, A. Janda, R. Arevalo, J. Pastor, I. Zuriguel, A. Garcimartín and D. Maza, “The flow rate of granular materials through an orifice,” Granular Matter, vol. 9, p. 407–414, 2007.