







# Development of a Clay 3D Printing Pen



Santosh Kumar , Meshram Himanshu Dheeraj , Pankaj Kumar Singh ,  
Ravi Prakash Singh , Md. Meraz , and Pramod Kumar Jain 

## 1 Introduction

Additive manufacturing (3D Printing) is defined as a procedure in which a computer model object is formed by depositing the material in layered style on all surfaces of the sliced model (Fig. 1). A direct link to the machine is established a preparatory code for the CAD items to be printed from a CAD file, and no need for production planning is required. This generative-additive technology has evolved as a disruptive technology for producing complicated parts straight from a CAD model. It has altered the way items are designed, manufactured, distributed, and sold. In 2013, the market revenue of India's 3D printer was \$17 million, and by 2021, it has reached \$79 million, with applications in biomedical and education sectors growing at a faster rate than other areas [1].

The graphic standards use the digital model (CAD) once it has been obtained in the (.STL) format splitting the surfaces into a triangle element network (mesh) (as shown in Fig. 1b); as a result, triangular facets are used to simplify the representation of the object's internal and external surfaces. With the help of customized software, the model (say Fig. 1a) has been sliced into thin layers (as shown in Fig. 1b, c); the corresponding file is transmitted to the CNC 3D printer which prints (Fig. 1d) the original digital model by layering material on top of previous layers until it becomes a

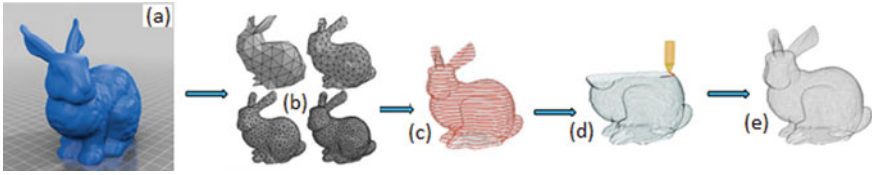
---

S. Kumar · M. H. Dheeraj · P. K. Singh (✉) · R. P. Singh · Md. Meraz  
Department of Mechanical Engineering, IIT (BHU), Varanasi 221005, India  
e-mail: [pankaj.krsingh.rs.mec18@itbhu.ac.in](mailto:pankaj.krsingh.rs.mec18@itbhu.ac.in)

S. Kumar  
e-mail: [santosh.kumar.mec@itbhu.ac.in](mailto:santosh.kumar.mec@itbhu.ac.in)

R. P. Singh  
e-mail: [ravips.rs.mec16@itbhu.ac.in](mailto:ravips.rs.mec16@itbhu.ac.in)

P. K. Jain  
Department of Mechanical and Industrial Engineering, IIT Roorkee, Roorkee, India  
e-mail: [pramod.jain@me.iitr.ac.in](mailto:pramod.jain@me.iitr.ac.in)



**Fig. 1** **a** CAD model, **b** versions of triangulated models, **c** slicing of one model, **d** layer-wise deposition of the model, and **e** Final printed physical model

real object (Fig. 1e). Various steps like slicing, (Gcode) file export, and clay extrusion are involved.

Turner et al. [2] described traditional fused deposition modeling (FDM) as “melting a filament that solidifies as it is pushed out of the nozzle.” The material options for FDM are limited to thermoplastics, with acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA) being the most widely used [3]. The extrusion-based 3D printing adds pastes and gels like clay, hydrogel, and silicone to the list of printable inks [4]. 3D printing is possible if the ink can be extruded through a nozzle and preserved its shape after deposition. Because of its adaptability, 3D printing may be employed with various applications, together with cell scaffolds [5] and flexible electronics [6].

An extrusion-based 3D printer has two primary components: the printer, which controls the movement and location of the nozzle, and the extruder, which regulates the material flow. Mainly extrusion system is categorized into conveying screw (delivers material from the hopper to the nozzle) [7], piston operated by a stepper motor (i.e., physical contact between extrusion and material) [8], and pneumatic (utilizes compressed gas as a driving force for extrusion) [4, 9]. The major material utilized in this project is Terracotta clay, which is inexpensive and frequently used for constructing clay models. Clay is a natural material made up mostly of fine-grained minerals, most of which are aluminosilicate plastics [10]. It is considered an inorganic substance. It controls the atmosphere by storing heat in the winter and releasing it in the summer, as well as cleansing the air around it by buffering humidity by taking moisture from the air during high humidity and releasing it at low humidity [11]. Furthermore, clay is reusable, recyclable, and emits less carbon than other construction materials, all of which contribute to a reduction in pollution [10].

## 2 Experimentation

The experiment was completed through various innovative and challenging stages from conceptualization to actual fabrication and from material selection to printing the models. These stages are extensively explained below.

## **2.1 Fabrication of the Clay 3D Printing Attachment**

The complete fabrication process of the clay 3D printing pen consists of an early prototype, modifications if needed, change in the initial prototype, and finally 3D printing with further changes.

### **2.1.1 Conceptualization and Early Prototype**

The current clay 3D printing attachment was conceptualized initially by taking motivation from a 3D printing pen which works by extruding heated plastic (ABS, PLA) that cools almost instantly into a solid, stable structure, that allows for freehand production of 3D printed things. So, the idea was to fabricate a clay 3D printing pen, i.e., a mechanism capable of extruding clay, and then develop freehand 3D models using clay as the extruding material.

After assembling all the parts shown in Table 1, the first prototype fabricated can be seen in Fig. 2a.

But, owing to the problems in working and size of the motor, one more gear was included in between the existing gears connected to the motor and lead screw. Also, a bearing was installed on the U-bracket, just above the gear facilitating the movement of the lead screw, for smooth functioning of the lead screw.

The new design of the pen after changes can be seen in Fig. 2b. Subsequently, a DC motor controller along with a speed regulator and control switch has been used to change the direction of rotation of the motor as seen in Table 2 for the manual operation of the pen.







### **2.1.2 Recommendations to Modify the Design**

Later, it was decided that rather than freehand printing the clay 3D printing pen should be mounted on a CNC machine and then perform automated 3D printing. So, to remove some limitations in the original design of the pen, a few modifications in the design of the pen were recommended.

In these modifications as shown in Fig. 3, it was suggested that the ram extrusion mechanism for clay extrusion be replaced by a continuous clay supply mechanism using an auger screw. This is because clay needs to be supplied after each outward stroke of the piston in the ram extrusion mechanism. Also, for continuous clay supply, there would be a tank mounted above the cylinder which can be filled with the desired amount of clay as required in the printing operation being performed.




But, implementing these recommended modifications meant the complete overhaul of the initial prototype with completely new parts. So, the recommendations were not implemented, and instead, it was decided to use the same prototype to carry out experiments with the necessary modifications required to make the pen rigid and correct the design flaws.

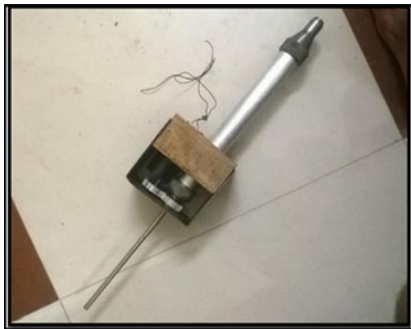
**Table 1** Different parts used in fabricating this pen are as follows

S. No.	Part name	Specifications	Function	Figures
1	Piston cylinder	Aluminum material with external diameter 31 mm and internal diameter 28 mm	To store the clay and later be extruded through a nozzle	
2	Cylinder cap	Mild steel material with external diameter 40.5 mm and internal diameter 31 mm	Connected to the piston cylinder and facilitates smooth axial movement of the lead screw to which the piston is connected and also prevents the lateral vibrations of the lead screw	
3	Gears	Material—Al Two gears of the same module and same no. of teeth—21	Useful in motion transmission from motor to the lead screw	
4	Screw nut	Material—bronze internal diameter—8 mm	Used to convert rotational motion of gear to translational motion of lead screw to push the piston	
5	Lead screw	Material—stainless steel Diameter—8 mm	The piston is attached at one end of the lead screw. The translational motion of the lead screw causes the piston to move axially in the piston cylinder to extrude the clay	
6	Nozzle	Mild steel material with internal diameter 31 mm and extruding diameter 4 mm	Extruding the clay pushed by the piston	

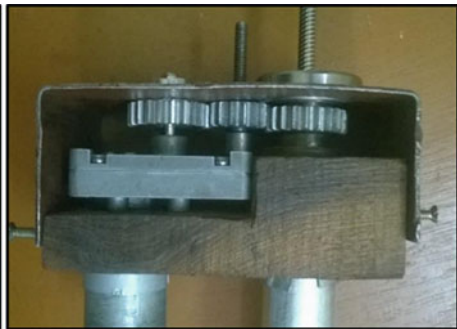
(continued)

**Table 1** (continued)

S. No.	Part name	Specifications	Function	Figures
7	Piston (slotted with O-ring rubber)	Mild steel material	Extruding the clay axially in the cylinder. Two O-ring rubber is fitted to minimize the friction between cylinder and piston and avoids the leakage of clay in the upward direction	
8	Motor	200 rpm with DC supply	Supply power to the whole setup and also supplies the power to lead screw via connected gears	
9	Wooden base with U-bracket		The whole assembly is mounted on a wooden base. The cylinder and motor were fixed in the base	




(a)



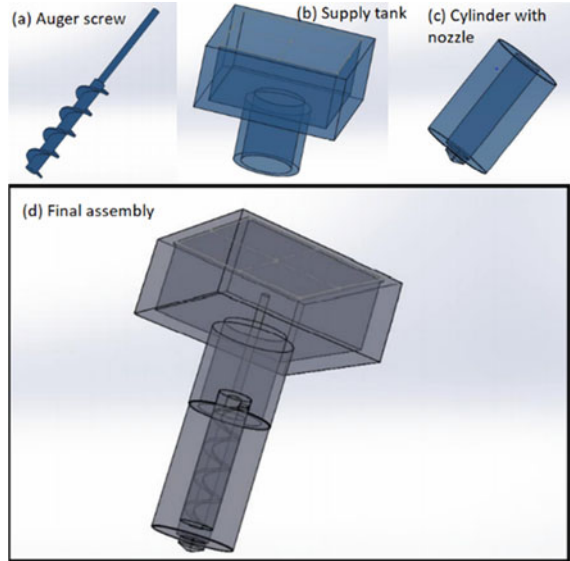
(b)

**Fig. 2** a First prototype of clay 3D pen and b clay 3D pen with changes in the prototype

**Table 2** Specifications of motor controller

Input voltage: DC 9–60 V Output voltage: Linear Output current: 0–20 A Speed regulation type: current Speed regulation range: 0–100% Size: approx. 92 × 52 × 36 mm	
---	--

**Fig. 3** Assembly of recommended modifications



### 2.1.3 Modifications in the Initial Prototype

Thus, to correct the initial design flaws and to make the pen more rigid, some modifications were made. The metal plates were used to reduce the vibrations and eccentric movements of the gear shafts. Glues and metal wires were used to attach various sections of the pen, such as the motor controller, control switch, speed regulator, and piston cylinder, to the wooden base. This was done to stiffen the structure and reduce vibrations during operation as shown in Fig. 4.

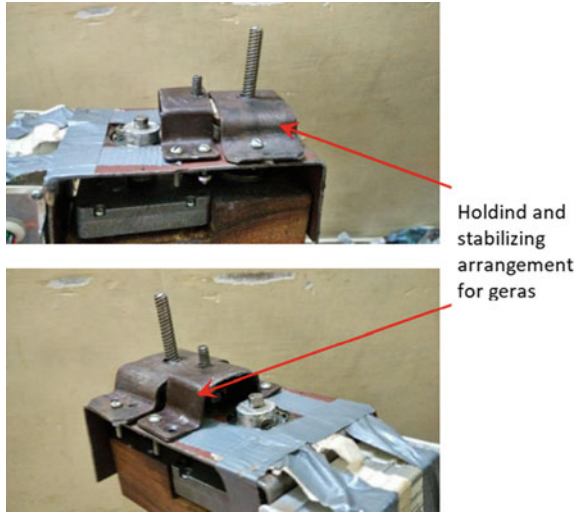
After these modifications, the 3D printing attachment was sufficiently rigid and stable. But, controlling the speed of pistons via motor speed control remained a bigger concern. The torque generated by the motor at slow speeds was not sufficient to extrude the clay. It still could extrude the clay at higher speeds, but the clay flow was too high to print anything as the feed rate of CNC has its limitations.

### 2.1.4 Additional Adjustments to the 3D Printing Attachment

Thus, the better torque control for piston movement was the only solution, and to do so, the DC motor was replaced with a servo motor (specification shown in Table 3).

The torque control capacity of the servo motor is far better than that of the DC motor, and it can be easily controlled through the same software which runs the CNC machine; so, the concerns of syncing the speeds of CNC and clay extrusion easily got solved. The slotted pipe which was used to stop the lead screw from rotating got the better alternative of two vertical rods of steel.

**Fig. 4** Holding and stabilizing arrangement for gears



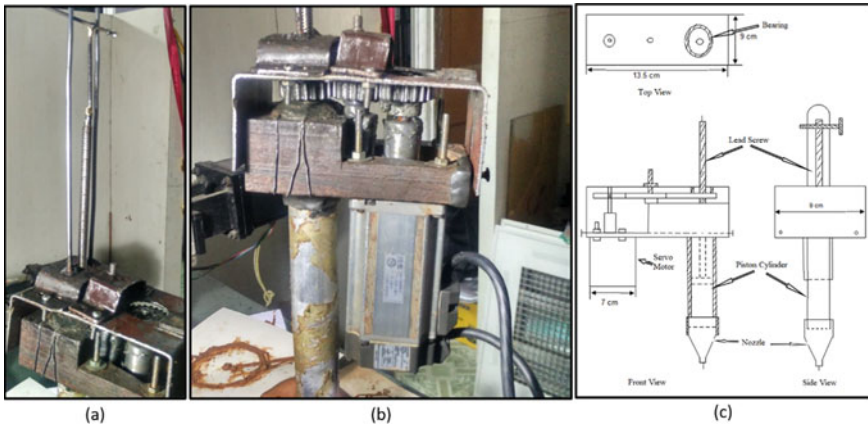
**Table 3** Specifications of servo motor

Input 3 $\phi$ AC 106 V 2.6 A	
Rated output 0.4 kW	
Rated revolution 3000 RPM	

This mechanism is more rigid, stable, and strong as compared to the pipe with the slot as shown in Fig. 5a. After making so many modifications to make the 3D printing attachment more rigid and with better control capability, it was ready in its final form as shown in Fig. 5b, c and ready to 3D print different models.

## 2.2 Slip Formation

All materials (terracotta clay, water, methylcellulose, and bentonite clay) are mixed well to have a homogeneous mixture. Normal tap water is added in the amount of 15–30% of the mass of clay taken. The water is added slowly in little amounts until the desired viscous mixture is obtained. A methylcellulose powder is added in the very small amounts of 2–4% of the mass of clay. It acts as a binder in the slip as the clay mixture must stay together while it is printed. Bentonite clay powder is also added in very small amounts of 2–5% of the mass of clay. Bentonite is added to increase plasticity and help in setting the extruded clay as early as possible. All of the ingredients are thoroughly combined to ensure that they are evenly distributed



**Fig. 5** a Two rods to prevent the leadscrew from rotating, b final assembly of clay 3D printing attachment, and c line diagram of 3D printer assembly

throughout the mixture. This slip is then poured into the piston cylinder and pressed down hard to prevent air from being trapped and causing discontinuous clay extrusion through the nozzle. The slip is then forced through the nozzle by a piston at the required speed to 3D print the desired model.

### 2.3 CNC Machines with Their Preparatory Codes

To 3D print, a model, the software (CAMSOFT) needs to be provided a CNC code for the model, which then interprets the code and guides the CNC machine through each step to generate the geometry of the object for which the code was written. The CNC machine can be programmed in two different ways: absolute coordinate programming and incremental coordinate programming.


The absolute coordinate system is employed by the CNC machine in this project. As a result, the programs were built to print various models. The specifications of the CNC machine are shown in Table 4.

### 2.4 3D Printing Parameters for Different Models

After all of the operations were finished, including attachment fabrication, CNC code writing, slip creation, and clay loading in cylinder arrangement, on the CNC machine, several 3D printing trials of diverse models were conducted as shown in Fig. 6a, b. The printing parameters like layer thickness, the width of each layer, and speed of

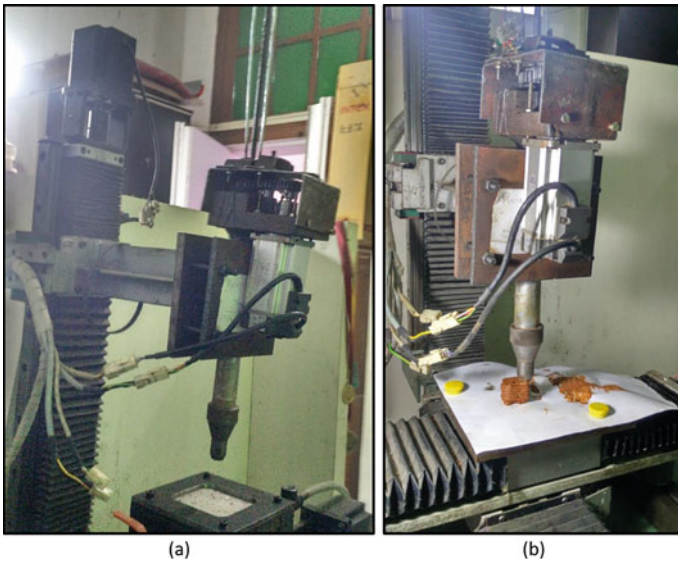


**Table 4** CNC machine specifications

Machine type: CNC (6 axes) with 8-axis controller	
Stepper motor—2.8 V, 4.5 A, 3000 rpm, 1.8°/step	
Spindle speed: 3000 RPM	
Maximum travel: X—49 cm, Y—49 cm, Z—60 cm	
Size of table: 20 × 15 × 2 cm	
Machine weight: 150 kg	
Machine resolution:0.01 mm	

the piston (in terms of rpm of the lead screw and axial increment of piston/length of the layer printed) were considered.

The experimented results, i.e., the different models printed and the effects of printing parameters on final parts are shown in the results and discussions section.



**Fig. 6** a 3D printing attachment mounted on CNC machine, and b Clay 3D printing of a model

### 3 Results and Discussion

#### 3.1 3D Printed Models

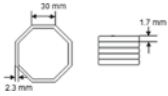


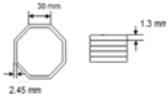

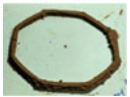
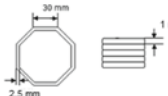
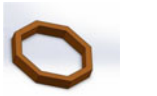

Different models were 3D printed using G-codes for each geometry with suitable dimensions as shown in Table 5.

**Table 5** Line diagram, CAD model, printing parameters, and fabricated different models

Different models	Line diagram	CAD model	Printing parameters	Fabricated diagram
Model 1			Layer thickness—2 mm, leadscrew—27 rpm, axial increment/length of the layer—1 mm/40 mm, road width—6 mm	
Model 2			Layer thickness—3 mm, leadscrew—27 rpm, axial increment/length of the layer—1 mm/40 mm, road width—6 mm	
Model 3			Layer thickness—3 mm, leadscrew—27 rpm, axial increment/length of the layer—1 mm/40 mm, road width—5 mm	
Model 4			Layer thickness—2 mm, leadscrew—6 rpm, axial increment/length of the layer—0.2 mm/30 mm, road width—3.4 mm	
Model 5			Layer thickness—2 mm, leadscrew—3 rpm, axial increment/length of the layer—0.1 mm/30 mm, road width—2.2 mm	

(continued)

**Table 5** (continued)

Different models	Line diagram	CAD model	Printing parameters	Fabricated diagram
Model 6			Layer thickness—1.7 mm, leadscrew—3 rpm, axial increment/length of the layer—0.1 mm/30 mm, road width—2.3 mm	
Model 7			Layer thickness—1.3 mm, leadscrew—3 rpm, axial increment/length of the layer—0.1 mm/30 mm, road width—2.45 mm	
Model 8			Layer thickness—1 mm, leadscrew—3 rpm, axial increment/length of the layer—0.1 mm/30 mm, road width—2.5 mm	

Model 1 was produced by extruding clay through a CNC machine’s 3D printing attachment. Only three layers were printed to see if the pen could extrude the clay or not. The nozzle was 4 mm in diameter. As a result, the road was wider. The water content in this area was roughly 25–26%.

To avoid the problem of clay spreading more than desired, the nozzle diameter was lowered to 4 mm, and the water content was reduced to 20–22% for model 2. The attachment’s ability to print diverse geometries with thick and broad layers with greater strength was demonstrated by the continuous printing of several layers.

When compared to the previous model, the nozzle diameter for model 3 was 2.5 mm, resulting in a reduction in road width. While printing this model, the road width appeared to be good at first, but as more layers were printed, the problem of water content varying throughout the mixture became apparent. The clay extruded in the top levels contained less water than the clay extruded in the first three layers. For this model, it was discovered that a homogeneous mixture is required, with all contents evenly distributed throughout the mixture, particularly water.

Model 4 had an octagonal with a 2.5-mm nozzle diameter and a 30 mm length on each side. The geometry of the models was kept the same from model 4 onward so that additional characteristics like road width, layer thickness, and piston speed could be compared. At a piston speed of ‘0.2 mm increment for the 30 mm length of layer printed,’ clay extrusion was quick in this model, resulting in a wider road, which was not desired. As a result, the piston speed had to be reduced.

For model 5, the road width and piston speed were decreased to the previous model and realized that clay extrusion was too slow at low piston speed to continuously fill the layer height of 2 mm. In addition, the successive layers were unable to adhere adequately. The piston speed was low enough that the tiny layers of clay were extruded as required. However, because of the slow rate, the layer height had to be lowered.

During model 5, the height of the layer was too high, but piston speed was too low. So, for model 6, the layer height was reduced keeping the piston speed the same. A layer thickness of 1.7 mm produced superior results for the specified piston speed. The thickness of the layers can be lowered further, and eventually, optimum parameters can be determined.

For model 7, the layer thickness was further lowered while all other parameters remained unchanged. When compared to the prior model, this one had improved attributes in several areas. The layers seemed to be well connected, giving the product strength. Road width was also small enough, as required in every model.

For model 8, to test the characteristics at very low layer height, the layer thickness was further lowered. It was found in this experiment that the layers were nearly blending. The successive layers heavily compressed the prior layers, causing the material to leak out between them.

### 3.2 Optimization of Printing Parameters

As can be seen in the 3D printing of numerous models described above, little alterations in the value of individual parameters cause changes in remaining parameters that alter the final product's attributes such as strength. These modifications also affect the way clay is extruded layer by layer, as well as the ability of these layers to bind together.

As a result, by comparing the values of each model's parameters and observing the printed goods, we were able to quickly establish the optimal values for the parameters, resulting in a superior 3D printed product with better properties as shown in Table 6.

The flow of clay through the nozzle fluctuates when the nozzle diameter is changed, according to the law of continuity. To manage the speed of clay flowing through the nozzle, the piston speed should be adjusted in tandem with the nozzle diameter.

**Table 6** Optimized printing parameters

Diameter of nozzle	2.5 mm
Content of water	18–20%
Height of layer	1.3 mm
Road width	2.45 mm
Piston speed	0.1 mm increment for the 30 mm length of layer printed

The optimal values of several parameters that might be picked for any other printing process were provided in Table 6 after researching and witnessing the 3D printing of the preceding models.

## 4 Conclusions

3D printing is a rapidly rising technology, and the same is true with the 3D printing industry. Thus, the theoretical investigation of numerous 3D printing technologies as well as the possibility of combining them with additional technologies and different materials is necessary, in addition to their practical, operational prototypes being fabricated and evaluated to check the theoretical results. The relevance of the theoretical results in a particular surrounding can only be verified by the practical results of the same type.

The goal of this research was to fabricate the clay 3D printing attachment which could be mounted on the CNC machine and then perform various experiments to generate a set of printing parameters that can give the best results for this combination of 3D printing attachment and the CNC machine. The results obtained are given below:

1. After numerous revisions to the original prototype, the 3D printing attachment was successfully constructed in its current form. The clay-filled attachment was then rigidly attached to the CNC machine to perform printing operations.
2. When the piston speed is modified, the amount of clay extruded through the nozzle changes, causing the road width to alter.
3. Changing the layer height modified the road width and, depending on the degree of compression generated by the nozzle, it also affected binding between consecutive layers.
4. The clay flow rate through the nozzle and the thickness of the layers were both modified by changing the nozzle diameter. As a result of the change in nozzle diameter, modifications in piston speed were required to keep printing at the optimal rate.
5. Following the analysis of the outcomes of numerous trials, a set of printing parameters was developed that can improve printing results.

**Acknowledgements** The authors express their sincere thanks to M.Tech.IDD students (2018 batch) of *Department of Mechanical Engineering, IIT (BHU) for conducting experiments and devote their deepest gratitude to UGC, New Delhi, India for funding the project with F. No31-50/2005 (SR-) dated 01-Sep-2009.*

## References

1. 6Wresearch Homepage. <https://www.6wresearch.com/press-release/india-3d-printer-market-2015-2021-share-news-forecasts-size>.
2. Turner, B., Strong, R.A., Gold, S.: A review of melt extrusion additive manufacturing processes: I. Process design and modeling, *Rapid Prototyp. J.* **20**, 192–204 (2014)
3. Kuo, C.C., Liu, L.C., Teng, W.F., Chang, H.Y., Chien, F.M., Liao, S.J., Kuo, W.F., Chen, C.M.: Preparation of starch/acrylonitrile-butadiene-styrene copolymers (ABS) biomass alloys and their feasible evaluation for 3D printing applications. *Compos. B Eng.* **86**, 36–39 (2016)
4. Hölzl, K., Lin, S., Tytgat, L., Van Vlierberghe, S., Gu, L., Ovsianikov, A.: Bioink properties before, during and after 3D bioprinting. *Biofabrication* **8**, 32002 (2016)
5. Ouyang, L., Yao, R., Zhao, Y., Sun, W.: Effect of bioink properties on printability and cell viability for 3D bioplotting of embryonic stem cells. *Biofabrication* **8**, 35020 (2016)
6. Shin, S.R., Farzad, R., Tamayol, A., Manoharan, V., Mostafalu, P., Zhang, Y.S., Akbari, M., Jung, S.M., Kim, D., Comotto, M., Annabi, N., Al-Hazmi, F.E., Dokmeci, M.R., Khademhosseini, A.: A bioactive carbon nanotube-based ink for printing 2D and 3D flexible electronics. *Adv. Mater.* **28**, 3280–3289 (2016)
7. Wang, L., Zhang, M., Bhandari, B., Yang, C.: Investigation on fish surimi gel as promising food material for 3D printing. *J. Food Eng.* 1–8 (2017)
8. Li, W., Ghazanfari, A., Leu, M.C., Landers, R.G.: Methods of extrusion on demand for high solids loading ceramic paste in freeform extrusion fabrication. *Int. Solid Freeform Fab. Symp.* 332–345 (2015)
9. Hinton, T.J., Jallerat, Q., Palchesko, R.N., Park, J.H., Grodzicki, M.S., Shue, H.-J., Ramadan, M.H., Hudson, A.R., Feinberg, A.W.: Three-dimensional printing of complex biological structures by freeform reversible embedding of suspended hydrogels. *Sci. Adv.* **1** (2015)
10. Lourenco, P., Fernandes, F., Castro, F.: Handmade clay bricks: chemical, physical and mechanical properties. *Int. J. Archit. Heritage* (2010)
11. Ayadi, A.J., Soro, J., Kamoun, A., Baklouti, S.: Study of clay's mineralogy effect on rheological behavior of ceramic suspensions using an experimental design. *Int. J. Recent Res.* 374–385 (2013)