© Universiti Tun Hussein Onn Malaysia Publisher's Office

IJIE

http://penerbit.uthm.edu.my/ojs/index.php/ijie
ISSN : 2229-838X e-ISSN : 2600-7916

The International Journal of Integrated Engineering

An Effect of Screw Extrusion Parameters On a Pottery Model Forming by A Clay Printing Machine

Paphakorn Pitayachaval[1*], Thanakhan Baothong[1]

[1]School of Industrial Engineering, Institute of Engineering, Suranaree University of Technology, Nakhon Ratchasima, 30000, THAILAND

*Corresponding Author

DOI: https://doi.org/10.30880/ijie.2022.14.06.004
Received 16 November 2020; Accepted 29 July 2021; Available online 10 November 2022

Abstract: This study presents the development of a clay printing machine based on the screw-based extrusion technique in which the clay is extruded through a circular nozzle to form clay model layer by layer. The developed machine consists of a material container for delivering system, a screw extruder for extruding clay through a circular nozzle and movement system. Traditionally, pottery models are formed by using paster mold or hand throwing, which require experience and proficient workers to form the complex pottery models. Therefore, the clay printing machine has been developed to improve pottery manually fabrication to automatic construction. To investigate a capability material deposition of the clay printing machine, the screw is the key component of an extruder that is the recommended choice for extrudability. The screw extrusion and machine parameters that effect on the appearance of clay filament were studies to find the optimal conditions of the machine. Analysis of variance (ANOVA) is used to analyze main effect parameters. The experimental results shown that the 6 mm nozzle diameter, 19 mm/s screw extruder velocity and 24 mm screw pitch were printing parameters for providing an appropriate appearance of clay filament. A mathematical model was formulated to propose the relationship between response and main effects with their interactions.

Keywords: Additive manufacturing, 3D printing, screw extrusion, clay

1. Introduction

Three-dimensional (3D) printing technologies are an additive manufacturing (AM) technique that is used to fabricate 3D objects from Computer Aided Design (CAD) data. 3D printing process as show in Fig. 1(a) starts with designing 3D objects by using 3D modeling software such as CAD or Rhino software. Then, 3D models are converted into a stereolithography (STL) that are sliced into horizontal layers. After that, the file is sent to the 3D printing machine in which 3D part is fabricated layer by layer on the machine. These technologies have been revolutionizing in prototyping industries and have been widely applied in variety industries, including aerospace, biomedical, construction and food. The flexibility in design, fabrication of complex geometries with high precision, material saving, low costs and personal customization are main advantages of this technology when compared with traditional fabrication methods such as matching or casting [1]. Another advantage of this technology is a wide range of materials such as metals [2], polymers [3], ceramics [4], concrete [5] and food [6] that are used to print physical parts. In 3D printing application, previously, 3D printing has been used to produce aesthetic and functional prototypes. More recently, 3D printing is effectively used to produce final products because it is able to 3D print small quantities of customized products with relatively low costs. Among a number of 3D printing technologies, extrusion-based additive manufacturing technique is a common manufacturing process that is increasingly used in the architecture and

*Corresponding author: paphakorn@g.sut.ac.th

construction industries [7]. In this technique, materials were extruded through a nozzle to from 3D objects by the successive layers of material.

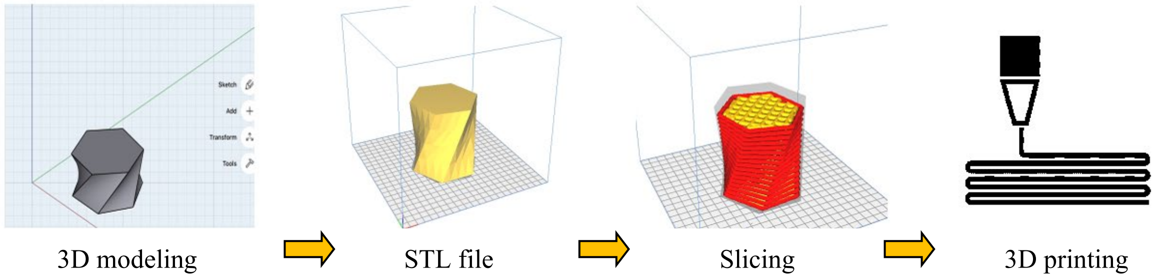


Fig. 1 - 3D printing process

Clay and concrete are mineral materials that are widely used to build architectural and structural components in the field of architecture and construction [8], [9]. 3D concrete printing (3DCP) is a process of fabricating concrete components, which the fresh concrete is extruded through a small pipe and nozzle to build structural components without formwork. This process is divided in three states as data preparation, concrete preparation, and component printing. The properties of fresh concrete in this process are extrudability and buildability, which have mutual relationship with the workability and the open time of concrete mix [10]. Similarly, fresh clay is generally fluid at the beginning. Then, the stiffness and strength increase when moisture is driven away with time. This material is viscous material and exhibit non-Newtonian behavior. Ram and screw extrusion are an extrusion-based additive manufacturing technique that the material is fed through a nozzle. In ram extrusion, the pressure is generated to force the material through a nozzle. The material flow is regulated by controlling the ram movement, which moves down to extrude material. In screw extrusion, a screw extruder is a machine which processes material by conveying it along a screw and forcing it through a nozzle by using pressure. The pressure developed in a screw extruder is affected by the screw geometry and the rheological property [11]. The screw is the key component of an extruder that is the recommended choice for controlled discharge of the material for further handling/processing [12]. Traditionally, ceramic and pottery products are formed by using paster mold or hand throwing. A general process of pottery forming is shown in Fig. 2. The basic steps include raw material preparation, forming and drying. The most of those products are produced based on a symmetry model. Ceramic and pottery artists require individual experience and proficient workers to form the complicated model. In pottery forming process, clay models are manufactured by using hand throwing on a pottery wheel. This process needs special control due to the clay models flexibly deform. Therefore, the clay printing machine has been developed to improve pottery manually fabrication to automatic construction. This machine has been modified based on the additive manufacturing. That is able to produce complicated models when compare with traditional fabrication methods.

This study presents the development of a clay printing machine based on the screw-based extrusion technique in which the clay is extruded through a circular nozzle to form clay model layer by layer. The developed machine consists of a material container for delivering system, a screw extruder for extruding clay through a circular nozzle and movement system. To assess a capability material deposition of the clay printing machine, nozzle diameter, screw extruder velocity, and screw pitch were investigated printing parameters to evaluate the clay filament in this experiment. This paper is organized as follow. The next section presents a process of the clay printing machine, a composition of mineral clay, experimental procedure and shows printing parameters. Then, experimental results were discussed to demonstrate main effect of printing parameters and lastly, conclusion is drawn.

Fig. 2 - A general pottery forming process

2. Literature Review

Extrusion-based additive manufacturing process is a process in which material is extruded through a nozzle. Extrusion-based additive manufacturing techniques can be classified into three categories based on the extrusion mechanism as shown in Fig. 3. Filament-based, plunger-based and screw-based extrusion have been used to extrude solid, liquid or viscosity materials [13]. Fused Deposition Modeling (FDM) or filament-based extrusion is a typical extrusion-based additive manufacturing technique in which a schematic of this technique is shown in Fig. 3(a). Polymeric material in the form of a filament is heated to reach semi-liquid state and then extruded though a nozzle for fabricating 3D model. This technique has limitations of application available materials in the form of a filament and instable flow of low viscosity material [14]. To avoid these limitations, plunger-based extrusion technique has been developed. A schematic of this technique is shown in Fig. 3(b), in which a heater is attached around a barrel to heat material into semi-liquid state. Then, the material is extruded though a nozzle by a linear plunger movement. In this technique, material degradation is main limitation that effects on material properties [15]. In order to overcome an existing limited range of printable materials in filament-based extrusion and material degradation in plunger-based extrusion, screw-based extrusion technique has been developed. A schematic of this technique is shown in Fig. 3(c). A screw extruder, a heating system and a nozzle are three main components of screw-based extrusion. A screw is used to extrude molten material through a nozzle by the rotating an electric device and 3D structure is fabricated [16]. Initially, Screw-based extrusion technique was introduced to fabricate physical models for rapid production of ceramic and polemic parts. Hong et al. [17] developed screw extruder printer to print high-viscosity material and conditions of screw extrusion were optimized. The attributes of viscosity material were indicated that particle size, shape, and high-viscosity flux composition are significant attributes of printing with high-viscosity material. Li et al. [18] investigated the extrusion performance of viscous ceramic paste by comparing three different extrusion methods (ram extruder, shutter valve, and auger extruder method). The results were shown that the auger extruder method shown the accuracy of the start and stop of extrusion and consistency extruded filament width than other methods. In recent years, Screw based extrusion has been applied to 3D food printing. Properties of food materials are important factor for application of extrusion techniques [19]. Rheological is an importance property of materials, which is provided for good extrudability and stability. Liu et al. [20] designed the rheological properties of mashed potatoes with addition of potato starch to investigate printing behavior by using 3D food printer with screw-based extrusion. The result shown that mashed potatoes with addition of 2 % potato starch, with rheological properties: consistency index 188.4 (Pa.s^n), yield stress 312.16 (Pa) and proper elastic modulus displayed good extrudability and stability. In ceramic industry, extrusion-based technologies have been applied to fabricate ceramic products that are formed based on ceramic clay. Zhang and Yang [21] used ceramic 3D printer that extruded material through a nozzle by using compressed air to form ceramic product. The result shown that the printer fabricated rapidly a complex geometry with high precision when compare with traditional fabrication methods. Previously literatures that were mentioned, which highlighted on the applications of the extrusion-based additive manufacturing techniques for 3D model forming in several fields. However, there are few literatures that studied on the design of the screw extrusion for 3D model forming in pottery manufacturing process. In this paper, the clay printing with screw extruder was developed. To investigate a capability material deposition of the clay printing machine, the screw is the key component of an extruder that is the recommended choice for extrudability. The screw extrusion and machine parameters that effect on the appearance of clay filament were studies to find the optimal conditions of the machine.

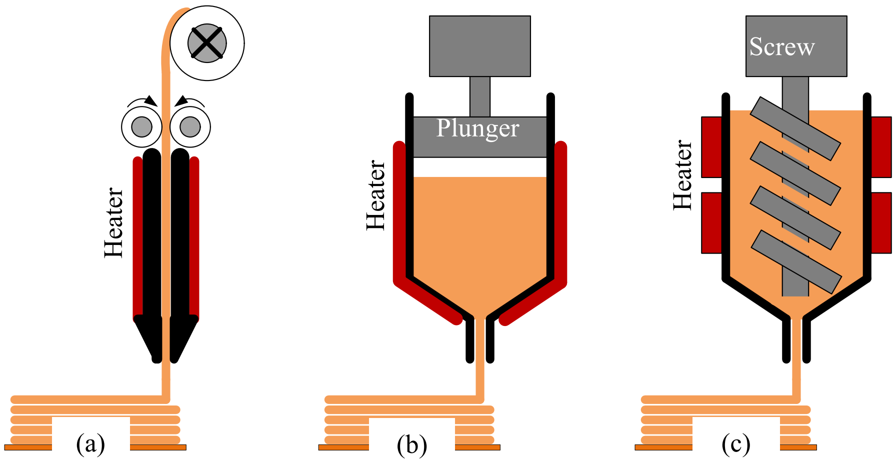


Fig. 3 - The extrusion mechanisms (a) filament-based extrusion; (b) plunger-based extrusion; (c) screw-based extrusion

3. Method and Material

3.1 The Clay Printing Machine

The clay printing machine is a machine to construct clay model layer-by-layer based on additive manufacturing. The principle of this machine is the deposition of materials through a nozzle in order to form 3D parts without mold and die. The schematic of the clay printing machine composed of three major components, as illustrated in Fig. 4: (a) a material container for delivering system, (b) a screw extruder for extruding clay through a circular nozzle and (c) the movement system for moving a nozzle in X and Y directions, in which these components have been controlled by a step motors via Computer Numerical Control (CNC) programming. The workspace of this machine is a 200 mm x 200 mm x 300 mm (width x length x height). To operate the clay printing process, a pottery clay was contained in a material container, which is pressed by a stepper motor through a tube into a screw extruder to pass a circular nozzle to deposit on a platform. The clay filaments were deposited layer-by-layer and bond each layer together to form a designed model. The start, stop and flowrate of clay printing are controlled by the screw rotation.

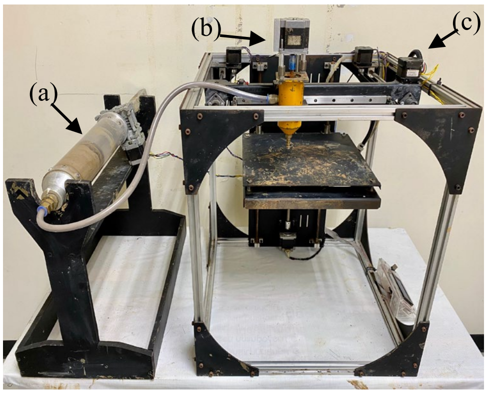


Fig. 4 - The clay printing machine (a) material container; (b) screw extruder; (c) movement system

3.2 Material

The consideration material is Dan Kwian clay in which a traditional material in north eastern of Thailand normally has been used to form traditional pottery. Dan Kwian clay has small particle sizes and high-plasticity which is easily formed into pottery models [22]. The main mineral compositions of Dan Kwian clay are quartz (45.7 wt%), kaolinite (42.3 wt%) and feldspar (5.6 wt%) [23].

3.3 Experimental Procedure

To assess a capability material deposition of the clay printing machine, fixed variables are screw length, internal diameter of screw, external diameter of screw and helix angle while a response variable is an extruded clay diameter, as presented in Table 1. In order to control diameter of clay filament, the investigated parameters are nozzle diameter (5, 6, 7 mm), screw extruder velocity (14, 19, 24 mm/s) and screw pitch (18, 24 mm), as presented in Table 2. There were 18 experiment groups (3 nozzle diameter x 3 screw extruder velocity x 2 screw pitch). Each group composed of 20 extruded clay filaments in which each length of extruded clay filament is 100 mm as shown in Fig. 5(a). However, the distance between platform and nozzle were also equal to the nozzle diameter. The width of extruded clay filaments was measured by using digital microscope, as shown in Fig. 5(b). The expected width of clay filaments is equaled to the extruded nozzle diameter. Since there are several screw types widely used in industry, the design of screw diameter, screw length, screw pitch and pitch angle depend on material characteristics, capacity required or conveying distance. The screw extruders were designed based on a principle of basic conveyor flight and pitch types. To investigate the effect on the variation of screw pitch, there are two screw types to apply for experiment as shown in Fig. 6: the short pitch, single flight screw is commonly used for paste material specially in an inclined and vertical screw conveyor applications. This screw pitch is equal to 2/3 screw diameter as shown in Fig. 6(a). This parameter was applied to control flow rate of extruded material. Besides, the half pitch, single flight screw is used for handling fluid materials. This screw pitch is equal to 1/2 screw diameter as shown in Fig. 6(b).

Table 1 - Experiment parameters

Fixed parameter	Value
Screw length	75 mm
internal diameter	16 mm

external diameter	36 mm
Response variable	**Value**
Clay filament diameter	measure

Table 2 - Printing parameters

Parameter	Value	Unit
Nozzle diameter (*D*)	5, 6, 7	mm
Screw extruder velocity (*V*)	14, 19, 24	mm/s
Pitch (*P*)	18 (the half pitch) 24 (the short pitch)	mm

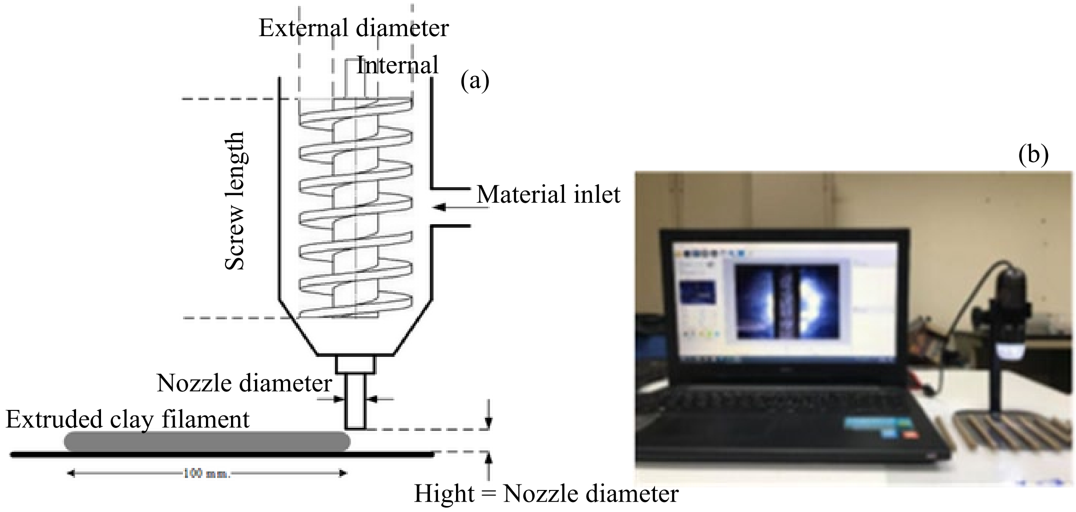


Fig. 5 - Experimental process (a) schematic diagram of extrusion clay process; (b) digital microscope

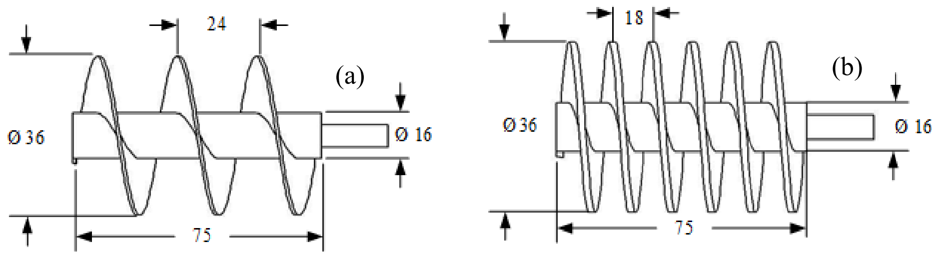


Fig. 6 - Hand throwing method

3.4 Statistical Analysis

Design of Experiment (DoE) method was applied to analyze the effect of input parameters (factors) on the width of the extruded clay filament (response variable). Analysis of variance (ANOVA) and mean comparison were processed with Minitab software (Minitab® 18.1: © 2017 Minitab, Inc. All rights reserved). Differences of $p < 0.05$ were determined to be significant.

4. Results and Discussion

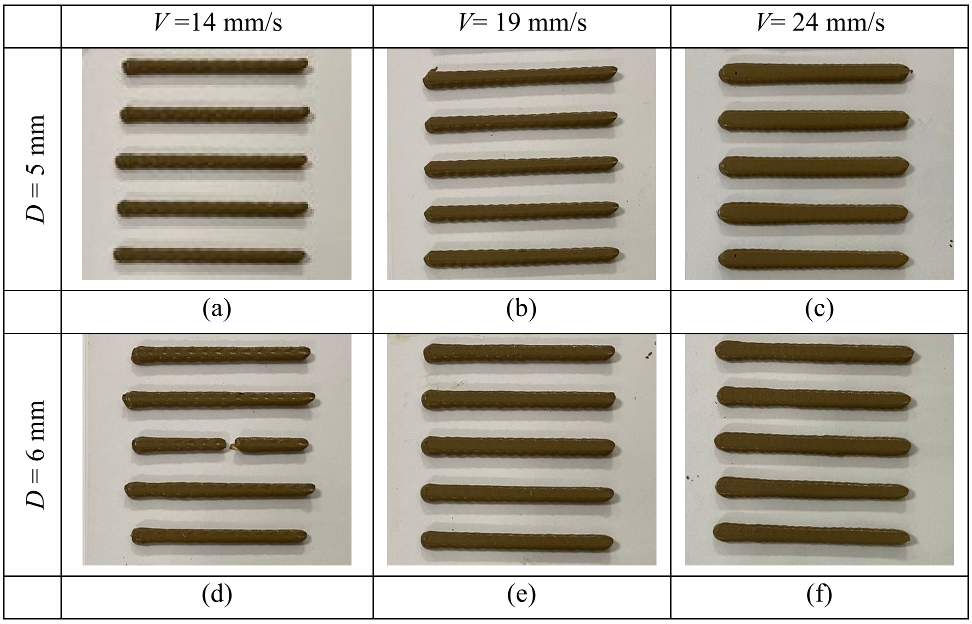
To evaluate the influence of nozzle diameter, screw extruder velocity and screw pitch on the clay filament, the straight-line tests were conducted where all the lines were printed from right to left. Fig. 7 and 8 show the clay filaments of different extrusion parameters. While a nozzle height was set to the same size as the nozzle diameter. As observed in experimental results, the effect of screw extruder velocity and nozzle diameter on the printed lines was demonstrated low screw extruder velocity (14 mm/s) shown small diameter than diameter of high screw extruder velocity (24 mm/s) with same nozzle diameter and screw pitch. In addition, low screw extruder velocity with large nozzle diameter (7 mm) led to discontinuous lines as shown in Fig. 7 (g) and 8 (g). The effect of two different pitch demonstrated the difference surface roughness. A 18 mm screw pitch presented wavy lines which exhibited the roughness surface as illustrated in Fig. 7, while a 24 mm screw pitch shown the straight lines which present smoothest surface as shown in Fig. 8. The 6 mm nozzle diameter, 19 mm/s screw extruder velocity and 24 mm screw pitch were suitable parameters to provide good appearance of clay filament. Each clay filament was measured the width. Then, DoE method was applied to analyze the effect of input parameters on the width of the clay filament. According to the ANOVA analysis, as shown in table 3. The nozzle diameter, the screw extruder velocity and the screw pitch are highly significant factors due to P values less than 0.05, as well as the interaction between the nozzle diameter and the screw pitch and the interaction between the nozzle diameter and the screw extruder velocity. The nozzle diameter, the screw extruder velocity and the screw pitch are main effect factors that were plotted in Fig. 9(a). The nozzle diameter and the screw extruder velocity effects were positive on the diameter of clay filaments. When increasing of these two factors, the diameter of clay filaments were increased. While the screw pitch effect is negative. However, main effects do not have much meaning when they are involved significant interactions. Therefore, it is always necessary to examine interactions that are important. The interaction between the nozzle diameter and the screw pitch was plotted in Fig. 9(b). This interaction illustrated that the screw pitch has large effect when the nozzle diameter is 5 mm, and has small effect when the nozzle diameter is 6 and 7 mm. The 6 mm nozzle diameter and 24 mm screw pitch seem most effective. The interaction between the screw extruder velocity and the nozzle diameter was plotted in Fig. 9(b). This interaction illustrated that the screw extruder velocity has small effect for each level of the nozzle diameter. The middle level of screw extruder velocity shown the best performance. A normal probability plot of the residuals was shown in Fig. 9(c). The points on this plot lie a similar straight line. Therefore, the residuals were considered to be a normal distribution. There are no tendency. So, these plots conclude that the regression model is suitable interpretation. To relate the relationship between the printed diameter and significant factors, equation (1) is a multiple linear regression model that are used to formulate this relationship.

$$\gamma = \beta_0 + \beta_1 \chi_1 + \beta_2 \chi_2 + \ldots + \beta_k \chi_k + \varepsilon \qquad (1)$$

Where γ is a response variable, χ_j , j=0,1,…k are independent variables, β_j , j=0,1,…k are regression coefficient, and ε is an error term. According to the ANOVA analysis by Minitab, the fitted regression model with terms and interactions can be defied as follows equation (2).

$$\gamma = 4.165 - 0.3109\chi_1 - 0.112\chi_2 + 0.1868\chi_3 + 0.04642\chi_1\chi_2 - 0.01659\chi_2\chi_3 \qquad (2)$$

Where γ is a printed diameter, χ_1 is a screw pitch, χ_2 is a nozzle diameter, and χ_3 is a screw extruder velocity. The R-sq. value of the above model is 83.51% which indicate a suitable accuracy.



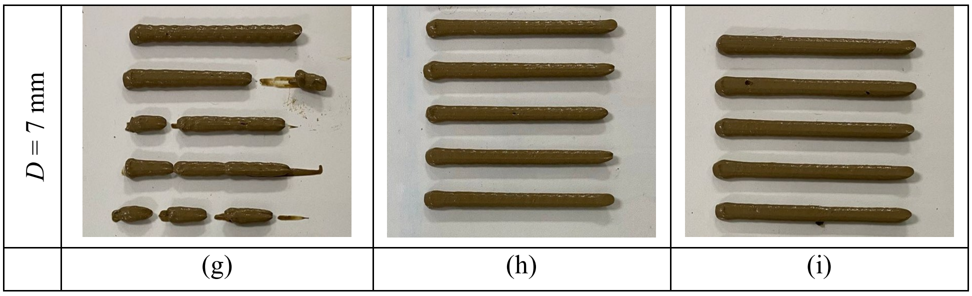


Fig. 7 - Clay filaments for 18 mm screw pitch with different nozzle diameter and screw extruder velocity

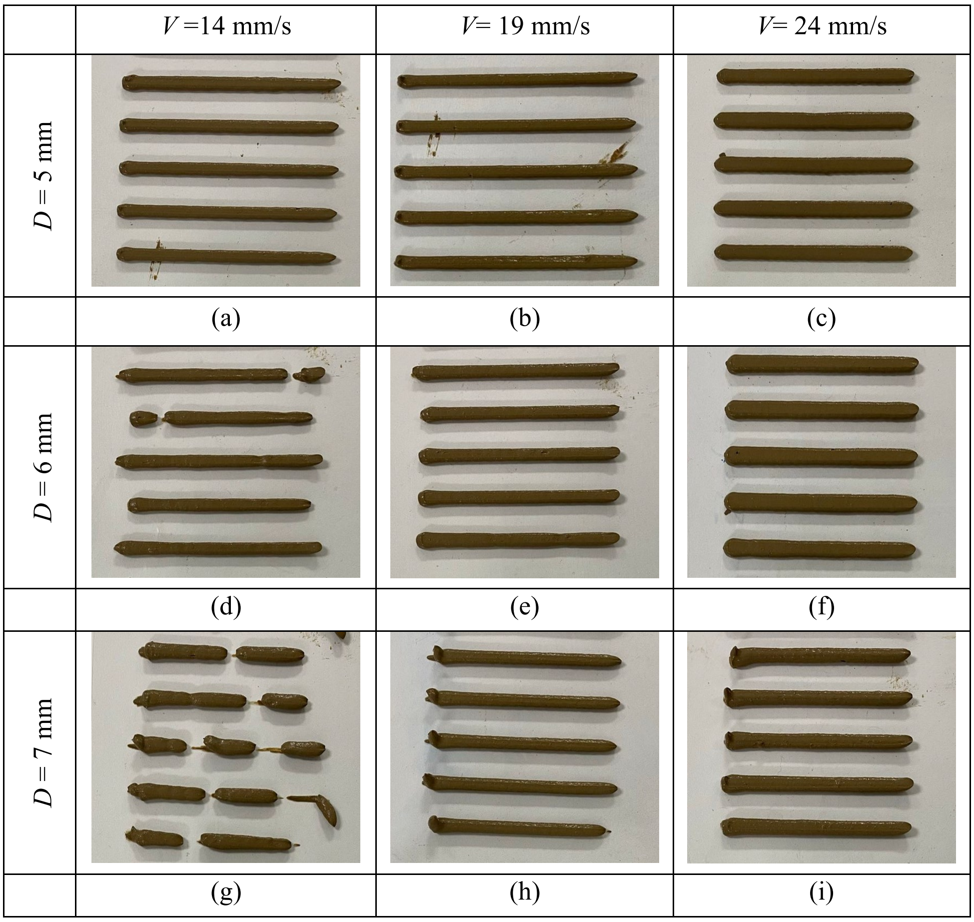
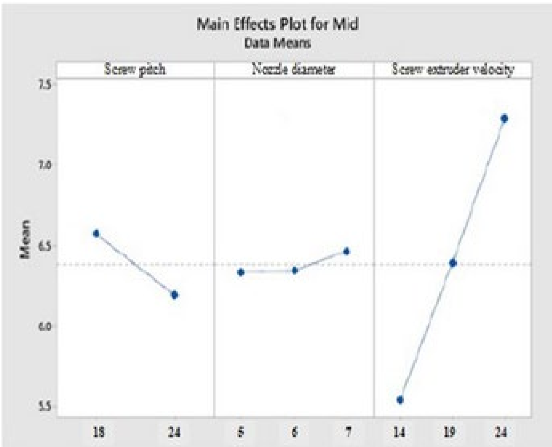


Fig. 8 - Clay filaments for 24 mm screw pitch with different nozzle diameter and screw extruder velocity

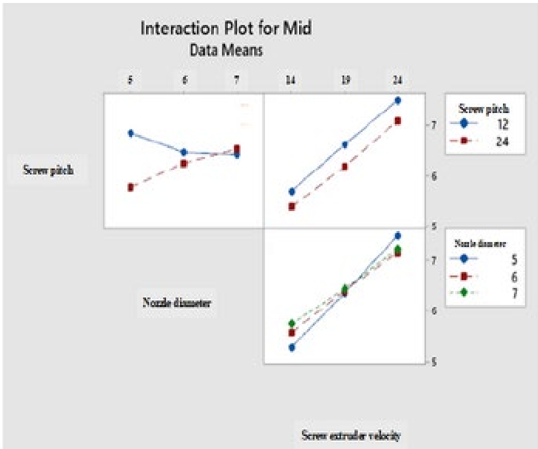
Table 3 - ANOVA result

Source	DF	ADJ SS	ADJ MS	F-Value	P-Value
Model	17	217.894	112.8173	110.39	0.000
Linear	5	187.900	37.5800	323.67	0.000
Pitch	1	12.759	12.7591	109.89	0.000
Nozzle Diameter	2	0.923	0.4615	3.97	0.020
Screw Extruder Velocity	2	173.617	86.8084	747.65	0.000
2-Way Interactions	8	24.407	3.0509	26.28	0.000
Pitch* Nozzle Diameter	2	18.708	9.3538	80.56	0.000
Pitch* Screw Extruder Velocity	2	0.263	0.1313	1.13	0.324
Nozzle Diameter * Screw Extruder Velocity	4	4.920	1.2301	10.59	0.000

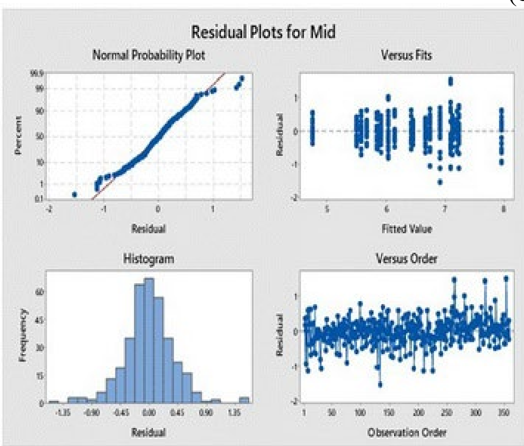
3-Way Interactions	4	2.011	0.5027	4.33	0.002
Pitch* Nozzle Diameter* Screw Extruder Velocity	4	2.011	0.5027	4.33	0.002
Errol	332	38.548	0.1161		
Total	349	256.441			



(a)



(b)



(c)

Fig. 9 - DoE analyze (a) main effect plots; (b) interaction plots; (c) residual plots

5. Conclusion

In traditional pottery forming process, clay models are manufactured by using hand throwing on a pottery wheel. This process needs special control and proficient individual experience of artist due to the clay models flexibly deform. In order to overcome these limitations, the clay printing machine was developed in this paper. This machine has been modified based on the screw-based extrusion technique. A screw extruder for extruding was mounted on the movement system, in which the system has been controlled by a step motors via CNC programming. The clay is extruded through a circular nozzle to form clay model layer by layer on the platform. To investigate a capability material deposition of the clay printing machine, the nozzle diameter, the screw extruder velocity and the screw pitch are parameters of the clay printing machine that were verified. As the experimental result, the nozzle diameter, the screw extruder velocity and the screw pitch are main effect parameters on the appearance of extruded clay filament for clay printing machine. A mathematical model was formulated to propose the relationship between response and main effects with their interactions. The R-sq. value of mathematical model is 83.51% which indicate a suitable accuracy. Therefore, the clay printing machine is presented in this study that can be used to produce pottery models.

Acknowledgement

This research is supported by the school of Industrial Engineering, Institute of Engineering, Suranaree University of Technology.

References

[1] Yang, F., Zhang, M., & Bhandari, B. (2017). Recent development in 3D food printing. Critical Reviews in Food Science and Nutrition, 57(14), 3145-3153. doi:10.1080/10408398.2015.1094732

[2] Singh, S., Ramakrishna, S., & Singh, R. (2017). Material issues in additive manufacturing: A review. Journal of Manufacturing Processes, 25, 185-200.

[3] Geng, P., Zhao, J., Wu, W., Ye, W., Wang, Y., Wang, S., & Zhang, S. (2019). Effects of extrusion speed and printing speed on the 3D printing stability of extruded PEEK filament. Journal of Manufacturing Processes, 37, 266-273. Doi: https://doi.org/10.1016/j.jmapro.2018.11.023

[4] Ghazanfari, A., Li, W., Leu, M., & Hilmas, G. (2017). A novel freeform extrusion fabrication process for producing solid ceramic components with uniform layered radiation drying. Additive manufacturing, 15, 102-112.

[5] Bos, F., Wolfs, R., Ahmed, Z., & Salet, T. (2016). Additive manufacturing of concrete in construction: potentials and challenges of 3D concrete printing. Virtual and Physical Prototyping, 11(3), 209-225. doi:10.1080/17452759.2016.1209867

[6] Wang, L., Zhang, M., Bhandari, B., & Yang, C. (2018). Investigation on fish surimi gel as promising food material for 3D printing. Journal of Food Engineering, 220, 101-108. Doi: https://doi.org/10.1016/j.jfoodeng.2017.02.029

[7] Mathur, R. (2016). 3D printing in architecture. IJISET-International Journal of Innovative Science, Engineering & Technology, 3(7), 583-591.

[8] Timothy, W., Ena, L., Lex, R., Norman, H., Fabio, G., Matthias, K., Robert, F. (2016). Digital Concrete: Opportunities and Challenges. RILEM Technical Letters, 1(0). doi:10.21809/rilemtechlett.2016.16

[9] Arnaud, P., Damien, R., Venkatesh Naidu, N., & Viktor, M. (2019). Extrusion of cement-based materials - an overview. RILEM Technical Letters, 3(0). doi:10.21809/rilemtechlett.2018.75

[10] Le, T. T., Austin, S. A., Lim, S., Buswell, R. A., Gibb, A. G. F., & Thorpe, T. (2012). Mix design and fresh properties for high-performance printing concrete. Materials and Structures, 45(8), 1221-1232. doi:10.1617/s11527-012-9828-z

[11] Benbow, J., & Bridgwater, J. (1993). Paste flow and extrusion.

[12] Waje, S. S., Thorat, B. N., & Mujumdar, A. S. (2007). Screw Conveyor Dryer: Process and Equipment Design. Drying Technology, 25(1), 241-247. doi:10.1080/07373930601161112

[13] Valkenaers, H., Vogeler, F., Ferraris, E., Voet, A., & Kruth, J.-P. (2013). A novel approach to additive manufacturing: screw extrusion 3D-printing. Paper presented at the Proceedings of the 10th International Conference on Multi-Material Micro Manufacture.

[14] Ngo, T. D., Kashani, A., Imbalzano, G., Nguyen, K. T. Q., & Hui, D. (2018). Additive manufacturing (3D printing): A review of materials, methods, applications and challenges. Composites Part B: Engineering, 143, 172-196. Doi: https://doi.org/10.1016/j.compositesb.2018.02.012

[15] Valkenaers, H., Vogeler, F., Voet, A., & Kruth, J.-P. (2013). Screw extrusion based 3D printing, a novel additive manufacturing technology. Paper presented at the COMA'13.

[16] Rane, K., & Strano, M. (2019). A comprehensive review of extrusion-based additive manufacturing processes for rapid production of metallic and ceramic parts. Advances in Manufacturing, 7(2), 155-173.

[17] Hong, S., Sanchez, C., Du, H., & Kim, N. (2015). Fabrication of 3D printed metal structures by use of high-viscosity cu paste and a screw extruder. Journal of Electronic Materials, 44(3), 836-841.

[18] Li, W., Ghazanfari, A., Leu, M. C., & Landers, R. G. (2017). Extrusion-on-demand methods for high solids loading ceramic paste in freeform extrusion fabrication. Virtual and Physical Prototyping, 12(3), 193-205.

[19] Godoi, F. C., Prakash, S., & Bhandari, B. R. (2016). 3d printing technologies applied for food design: Status and prospects. Journal of Food Engineering, 179, 44-54.

[20] Liu, Z., Zhang, M., Bhandari, B., & Yang, C. (2018). Impact of rheological properties of mashed potatoes on 3D printing. Journal of Food Engineering, 220, 76-82.

[21] Zhang, M., & Yang, L. (2016). Ceramic product forming technologies research based on 3D printing. IEEE Access, 4, 9345-9349.

[22] Srilomsak, S., Pattanasiriwisawa, W., Somphon, W., Tanthanuch, W., & Meethong, N. (2014). Effect of firing conditions on properties of Dan Kwian pottery. Suranaree J. Sci. Technol. Available from: http://ird. sut. ac. th/e-journal/Journal/pdf/1401718. pdf.

[23] Poowancum, A., & Horpibulsuk, S. (2015). Development of low cost geopolymer from calcined sedimentary clay. In *Calcined Clays for Sustainable Concrete* (pp. 359-364): Springer.