A DESIGN OF EXTRUDER PARAMETERS FOR THE PASTE EXTRUSION PROCESS

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วิทยานิพนธ์นี้สำหรับการศึกษาตามหลักสูตรปริญญาวิศวกรรมศาสตรดุษฎีบัณฑิต
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A DESIGN OF EXTRUDER PARAMETERS FOR THE PASTE EXTRUSION PROCESS

Suranaree University of Technology has approved this thesis submitted in fulfillment of the requirements for the Degree of Doctor of Philosophy.

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คำสำคัญ: การผลิตแบบเพิ่มเนื้อวัสดุ/เครื่องพิมพ์ขึ้นรูป 3 มิติ/กระบวนการอัดขึ้นรูป/ดินเหนียว/หัวฉีดแบบสกรู

กระบวนการผลิตผลิตภัณฑ์เครื่องปั้นดินเผาด้วยวิธีการขึ้นรูปโดยใช้แป้นหมุนเป็นกระบวนการผลิตแบบดั่งเดิม ซึ่งกระบวนการผลิตแบบดั่งเดิมนี้อาศัยทักษะฝีมือและความชำนาญของช่างปั้นในการปั้นขึ้นรูปผลิตภัณฑ์เครื่องปั้นดินเผา เนื่องจากในระหว่างขั้นตอนการปั้นเป็นรูปทรงแบบเครื่องปั้นดินเผาง่ายต่อการทรุดตัว อีกทั้งการใช้ฝีมือแรงงานในการผลิตซึ่งเป็นสาเหตุให้กระบวนการผลิตล่าช้าและปัจจุบันฝีมือแรงงานในพื้นที่ลดลง ดังนั้นงานวิจัยนี้จึงมุ่งเน้นการพัฒนาเครื่องพิมพ์ขึ้นรูปผลิตภัณฑ์เครื่องปั้นดินเผาโดยการประยุกต์ใช้เทคโนโลยีการขึ้นรูปแบบ 3 มิติ ซึ่งการขึ้นรูปด้วยเครื่องพิมพ์ขึ้นรูปแบบ 3 มิตินี้เป็นการขึ้นรูปผลิตภัณฑ์เครื่องปั้นดินเผาจากแบบจำลอง 3 มิติทางคอมพิวเตอร์ โดยดินวัสดุจะถูกอัดเข้าสู่หัวฉีดแบบกรู จากนั้นดินวัสดุถูกอัดและลำเลียงออกจากหัวฉีดโดยใช้การหมุนของสกรูเพื่อขึ้นรูปชิ้นงานทีละชั้นจนเป็นรูปร่างชิ้นงานที่สมบูรณ์ เครื่องพิมพ์ขึ้นรูปผลิตภัณฑ์เครื่องปั้นดินเผาแบบ 3 มิติประกอบไปด้วย 4 ส่วนประกอบที่สำคัญคือ ชุดกระบอกบรรจุดินวัสดุ (Material container), หัวฉีดแบบสกรู (Screw extruder), ฐานรองชิ้นงาน (Platform) และระบบการเคลื่อนที่ (Movement system) และได้ศึกษาปัจจัยของหัวฉีดแบบสกรูที่มีผลต่อการฉีดขึ้นรูปเส้นดินวัสดุ โดยมีปัจจัยที่ทำการศึกษาคือ ขนาดของเกลียวสกรู (Screw pitch), ความเร็วรอบสกรู (Screw velocity) และขนาดปลายหัวฉีด (Nozzle diameter) อีกทั้งได้ทำการวิเคราะห์โครงสร้างจุลภาคและองค์ประกอบทางเคมีของดินวัสดุ ผลการวิจัยพบว่าดินเหนียวดินด่านเกวียนมีคุณสมบัติที่เหมาะสำหรับนำมาขึ้นรูปด้วยเครื่องพิมพ์ขึ้นรูปผลิตภัณฑ์เครื่องปั้นดินเผาแบบ 3 มิติ และปัจจัยหลักทุกปัจจัยมีอิทธิพลต่อขนาดความกว้างของเส้นดินวัสดุอย่างมีนัยสำคัญ และยังมีอิทธิพลร่วมระหว่างขนาดของเกลียวสกรูกับความเร็วรอบสกรู, ขนาดของเกลียวสกรูกับขนาดปลายหัวฉีด และความเร็วรอบสกรูกับขนาดปลายหัวฉีดต่างก็มีอิทธิพลต่อขนาดความกว้างของเส้นดินวัสดุอย่างมีนัยสำคัญเช่นกัน โดยปัจจัยดังกล่าวสามารถสร้างแบบจำลองโมเดลทางคณิตศาสตร์แสดง

ความสัมพันธ์ระหว่างปัจจัยหลักและอิทธิร่วมของปัจจัยหลักต่อขนาดความกว้างของเส้นดินวัสดุด้วยสมการการถดถอยแบบเชิงเส้นพหุคูณ โดยมีค่า R^2 เท่ากับ 73.73% และมีค่า R^2_{adj} เท่ากับ 73.36% แสดงว่าแบบจำลองนี้เหมาะสมสามารถประมาณค่าขนาดความกว้างของเส้นดินวัสดุได้

สาขาวิชาวิศวกรรมอุตสาหการ

ปีการศึกษา 2564

ลายมือชื่อนักศึกษา ______

ลายมือชื่ออาจารย์ที่ปรึกษา ______

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Keyword: Additive manufacturing/3D printing/Extrusion process/Clay/Screw extruder

In the pottery forming process by using hand throwing on a pottery wheel, the proficient potter has been requiring because this process needs special control by human and the clay models is flexible to deform. To overcome these advantages, a clay printing machine has been developed based on the paste process in this research, in which the clay is extruded through a nozzle to form 3D models layer-by-layer. This machine consists of a material container, a screw extruder, a platform and the movement controlling systems via CNC programming. The main functions of the screw extruder are to compress and to convey of the clay through an extruded. Therefore, the appearances and the amount of the extruded clay filament are depended on a screw shape and a velocity of the screw rotation. Furthermore, microstructures and clay mineral compositions of clay were analyzed. To develop a capability of material deposition, a screw pitch, a nozzle diameter and a screw extruder velocity were investigated as the printing parameters, which were analyzed their effects on size the extruded clay filament and a quality of clay filament. The experimental results of the analysis of microstructures and clay mineral compositions were shown that Dan kwian clay is suitable to form by the clay printing machine. The experimental results of the analysis of variance were shown that the screw pitch, the nozzle diameter, the screw extruder velocity and their interactions were significant factors, which effected on the width of the extruded clay filament. Mover, the means width of the extruded clay filament were increased when the nozzle diameter and the screw extruder velocity were increased, whereas the screw pitch was decreased. In addition, a multiple linear regression model was formulated to describe the relationship between the width of the extruded clay filament and the significant factors. The R-squared (R^2) value of the model was 73.73% and an adjusted R^2 was 73.36%, which indicate a suitable accuracy.

School of Industrial Engineering

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Student's Signature ______________

Advisor's Signature ______________

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TABLE OF CONTANTS

TABLE OF CONTANTS (Continued)

Page

TABLE OF CONTANTS (Continued)

Page

TABLE OF CONTANTS (Continued)

Page

LIST OF TABLES

Table Page

LIST OF FIGURES

Figure Page

LIST OF FIGURES (Continued)

Figure Page

SYMBOLS AND ABBREVIATIONS

RP	=	Rapid prototype
3D	=	Three-dimension
AM	=	Additive manufacturing
CAD	=	Computer aided design
STL	=	Stereolithography
PTE	=	Piston type extrusion
STE	=	Screw type extrusion
WC	=	Water content
RPM	=	Revolutions per minute
FDM	=	Fused deposition modeling
RC	=	Robocasting
DIW	=	Direct ink writing
FEF	=	Freeze-form extrusion fabrication
ABEF	=	Aqueous-based extrusion fabrication
MEAM	=	Material extrusion-based additive manufacturing
ISO	=	International organization for standardization
ASTM	=	America society for testing and materials
ChocALM	=	Chocolate additive layer manufacturing process
CODE	=	Ceramic on-demand extrusion
CNC	=	Computer numerical control
USB	=	Universal serial bus
ABS	=	Acrylonitrile butadiene styrene
PLA	=	Polyactic acid
PC	=	Polycarbonate

SYMBOLS AND ABBREVIATIONS (Continued)

DoE	=	Design of experiment
ANOVA	=	Analysis of variance
XRD	=	X-ray diffractometer
SEM	=	Scanning electron microscopy
L_f	=	Feeding
L_c	=	Compression
L_m	=	Metering
L_b	=	Barrel length
L_s	=	Screw length
D_s	=	External screw diameter
C_d	=	Cylinder diameter
C_l	=	Cylinder length
B_d	=	External barrel diameter
B_i	=	Internal barrel diameter
B_l	=	Barrel length
N_l	=	Nozzle length
D	=	Barrel diameter
d	=	Internal screw diameter
S	=	Screw pitch
N	=	Nozzle diameter
V_s	=	Screw extruder velocity
h	=	Flight depth
w	=	Chanel width
L	=	Screw length
mL	=	Milliliter
mm	=	Millimeter
kg	=	Kilogram

SYMBOLS AND ABBREVIATIONS (Continued)

μm	=	Micrometer
mm/s	=	Millimeter per second
$\emptyset$	=	Helix angle
δ	=	Screw clearance
μ	=	Over all mean
ε	=	Experimental error
Y_{ij}	=	*j*th response taken under factor level *i*
$Y_{ijk,t}$	=	*t*th response taken under factor level *ijk*
τ_i	=	*i*th level factor A
β_j	=	*j*th level factor B
γ_k	=	*k*th level factor C
$(\tau\beta)_{ij}$	=	Interaction between τ_i and β_j
$(\beta\gamma)_{jk}$	=	Interaction between β_j and γ_k
$(\tau\beta\gamma)_{ijk}$	=	Interaction between τ_i , β_j and γ_k
$H1$	=	Null hypothesis
H_0	=	Alternative hypothesis
SiO_2	=	Quartz
$Si_2Al_2O5(OH)_4$	=	Kaolinite
$K_yAl_4(Si_{8-y}Al_y)O_{20}(OH)_4$, $1 < y < 1.5$	=	Illite

CHAPTER I

INTRODUCTION

1.1 Background

The emergences of new technological Rapid Prototypes (RP) have been growing extensively in recent year. The RP technologies are classified into two categories based on the manufacturing process into subtractive material and additive material. Subtractive manufacturing is a traditional process, in which materials is removed from initial shape to form the final models. Additive manufacturing (AM), commonly known as 3D printing is a non-traditional process that fabricate 3D models by adding material layer-by-layer directly from computer aided design (CAD) model. AM is defined as "a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies" (ISO/ASTM 52900 Additive manufacturing general principles terminology, 2015). AM processes can be classified into seven techniques: binder jetting, direct energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination, and vat photopolymerization as shown in Figure 1.1. These techniques have been revolutionizing in prototyping industries and have been widely applied in variety industries, including aerospace, biomedical, construction and food (Ngo, Kashani, Imbalzano, Nguyen and Hui, 2018). 3D printing process as show in Figure 1.2 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.

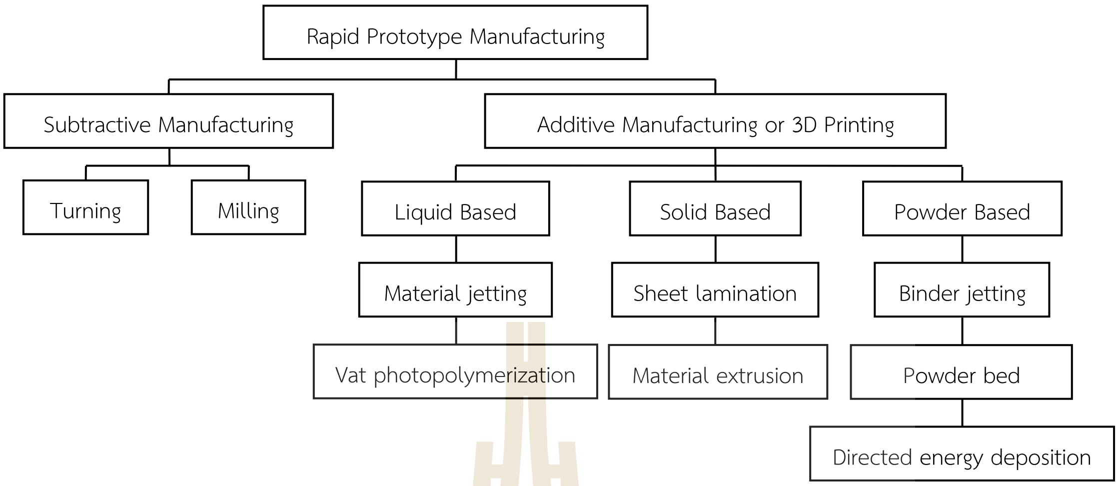


Figure 1.1 Classification of rapid prototype manufacturing processes

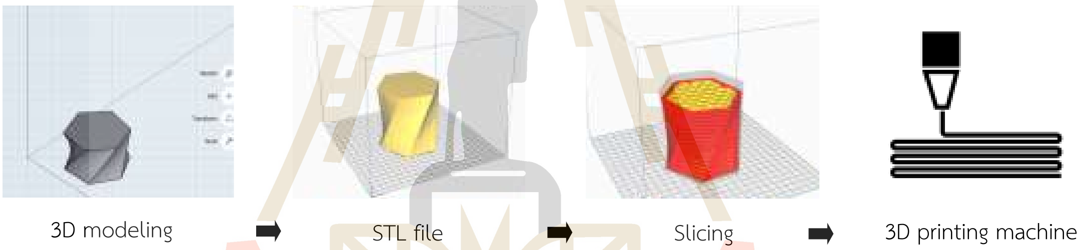


Figure 1.2 3D Printing process

3D Printing is an innovation which is becoming the main manufacturing process in many industries due to a flexible design and possible fabrication of complex geometry parts (Lu, Li and Tian, 2015). Compare with conventional manufacturing processes, the 3D printing is more efficient in terms of material usage and energy consumption because it fabricates the final products by adding martial (Peng, 2016). Previously, 3D printing has been used to produce functional prototypes. Nowadays, 3D printing is effectively used to produce final products because it is able to 3D print small quantities of customer requirement with relatively low costs (Berman, 2012). The transition from conventional prototyping to individual customer manufacturing has been interesting for the 3D printing application. However, the 3D printing technology has existing limitations include size limitation, high cost of 3D printing equipment and material (Chen, He, Yang, Niu and Ren, 2017; Huang, Liu, Mokasdar and Hou, 2013). General raw materials that can be printed by using the 3D printing processes are classified three categories based on the nature materials into liquid-based, solid-based and powder-based as shown in Figure 1.1. Because of the printable materials, the range of the 3D printing application is limitation to other fields. Then, new materials such as biomaterials, composite materials, smart material, ceramics materials and electronics materials have been developed and used for 3D printing applications (Lee, An and Chua, 2017). Paste is viscosity material have been interested to fabricate physical parts by using 3D printing technologies. The physical parts can be maintained after printing because of high viscosity materials. Paste is a mixture of powder and liquid which can be formed from many different substances. Pastes are formed by using extrusion methods in which it is necessary to know the paste properties that are used to determine printing conditions of 3D printer machines. High viscosity Cu pastes were formulated and printed by using 3D printer with a screw extruder to produce 3D metal structures and determine the printing conditions (Hong, Sanchez, Du, and Kim, 2015). The experimental results showed that the quality of the 3D metal structure shape and printing conditions depend on the viscosity of material. The piston type extrusion (PTE) method and food materials with different viscosities were investigated to optimize condition of viscosity, temperature, pressure and nozzle traveling speed (Kim, Eo and Cho, 2018). The experimental results showed that the material viscosity of 0.001-1000 Pa.S, the nozzle traveling speed 0.0015 and 0.002 m/s were the optimize printing conditions. The printability of the high viscosity ceramic pastes by using the screw type extrusion (STE) machine was studied to define the significant parameters extrusion process (Kim, Cho and Zielewski, 2019). The resultant of the study showed that water content in material (WC), revolutions per minute (RPM) and diameter of the nozzle tip (TIP) were significant parameters that effect to the 3D printability. There are many paste materials including food, metal and clay (Paphakorn and Thanakharn, 2021), in which the paste materials can be printed by using extrusion methods. The material extrusion is the additive manufacturing process is a process in which material is extruded through a nozzle. Main material extrusion-based additive manufacturing techniques can be classified into three categories as shown in Figure 1.3. Filament-based extrusion is one of the extrusion-based additive manufacturing techniques in which a schematic of this technique is shown in Figure 1.3 (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.

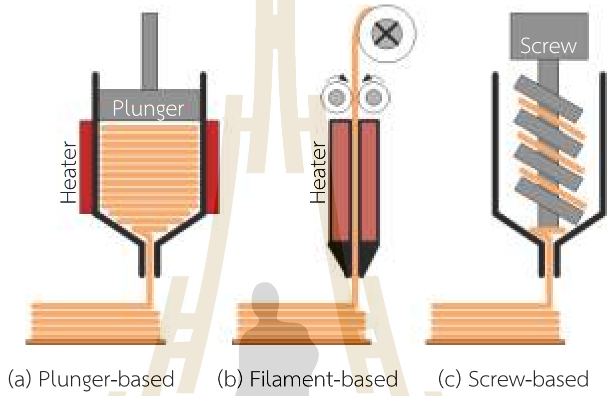


Figure 1.3 Extrusion-based additive manufacturing techniques

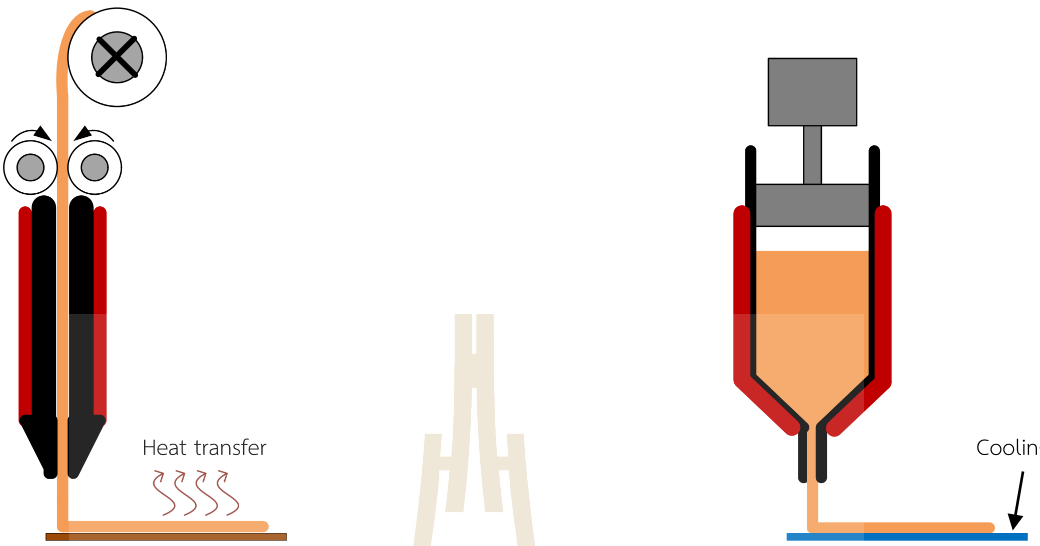
This technique has limitations of application available materials in the form of a filament and instable flow of low viscosity material (Ngo et al., 2018). To avoid these limitations, plunger-based extrusion technique has been developed. A schematic of this technique is shown in Figure 1.3 (b), in which 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 piston movement. In this technique, material degradation is main limitation that effects on material properties (Valkenaers, Vogeler, Ferraris, Voet and Kruth, 2013). In order to overcome an existing limited range of printable materials in filament-based extrusion and material degradation in piston-based extrusion, screw-based extrusion technique has been developed. A schematic of this technique is shown in Figure 1.3 (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. The screw is a key component for an extruder in which it is used to control the start and stop of extrusion.

Clay is a type of ceramic material, which is the paste material. Dan kwian clay, Lampang clay and Ratchaburi red clay are important raw materials that have been used to manufacture the ceramic pottery of Thailand. Red clay from Ratchaburi province in Western Thailand have been used to form pottery and garden ware. Ratchaburi red clay has high plasticity for forming ceramic bodies. However, the Ratchaburi red clay is very sticky and difficult to dry. Lampang clay is normally found in Lampang province in northern Thailand. Which has been used for the manufacturing of ceramic products. Dan kwian clay is the clay that normally found near the moon riverside in Dan kwian subdistrict, Chok Chai district, Nakhon Ratchasima province in Northeast Thailand. Dan kwian clay is raw material that is used to form Dan kwian pottery products. Those clays were analyzed to study microstructure, clay minerals and mineral compositions which are suitable for the clay printing machine. Dan Kwian pottery is a famous product of Nakhon Ratchasima province, Thailand in which it is a high viscosity material. Dan Kwian clay is raw material that is used to form Dan Kwian pottery products. The pottery products are formed by using hand throwing technique. A general process of Dan Kwian pottery forming is shown in Figure 1.4. The basic processes include raw material preparation, forming and drying. In forming process, clay models are produced by hand throwing on a pottery wheel. Potters require individual experience and proficient workers to form the model. This process needs special control due to the clay models flexibly deform.

Material preparation Forming Drying

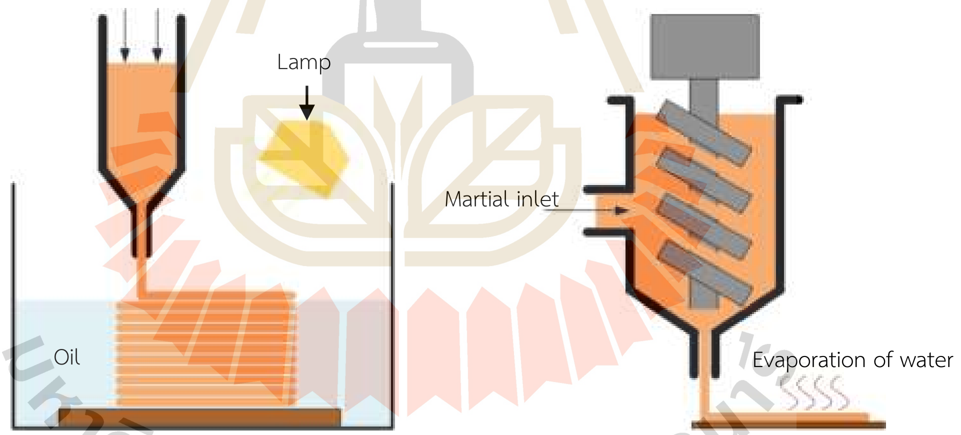
Figure 1.4 A general Dan Kwian pottery forming process

To improve pottery manual fabrication to automatic construction. This research presents the development of a clay printing machine based on material extrusion additive manufacturing technique, in which clay material is extruded through a circular nozzle by screw rotation to form clay model layer by layer without mold and die. The screw is used to control the start and stop of extrusion and the consistency of extruded clay filament. In the clay printing machine process, the method of solidification is different from the extrusion-based additive manufacturing techniques as shown in Figure 1.5 and 1.6. The material is extruded in a molted form at room temperature in the typical fused deposition modeling (FDM) process. Then, the molten material becomes to solid state by heat transfer process as shown in Figure 1.5 (a). In the freeze-form extrusion fabrication (FEF) process, aqueous-based ceramic or metal paste are deposited on a platform. The platform is set in a freezer space in which the extruded material is solidified to frozen solid as shown in Figure 1.5 (b). In the ceramic on-demand extrusion (CODE) process, the ceramic paste is deposited on a substrate located in a liquid oil tank as shown in Figure 1.6 (a). After completing each layer, the liquid oil is pumped into the tank to preclude water evaporation. Then, an infrared lamp is used to dry the extruded material. The solidification of clay printing machine process, the clay paste is extruded on a platform at room temperature The solidification of clay printing machine process, the clay paste is extruded on a platform at room temperature. The extruded clay is solidified by water evaporation process as shown in Figure 1.6 (b). The clay printing machine consists of a material container for delivering system, a screw extruder for extruding clay through a circular nozzle and movement system. The main functions of the screw extruder are controlling and conveyance of amount extruded clay material. To develop the capability material deposition of the machine, nozzle diameters, screw extruder velocities, and screw pitch were studied to design the screw extruder.



(a) The fused deposition modeling process (b) The freeze-form extrusion fabrication process

Figure 1.5 Diagram solidification process of fused deposition modeling and freeze-form extrusion fabrication process



(a) The ceramic on-demand extrusion process (b) the clay printing process

Figure 1.6 Diagram solidification process of ceramic on-demand extrusion and the clay printing process

1.2 Research objective

A research objective is to design the screw extruder on a paste extrusion process, in which the influences of screw pitch, nozzle diameter and screw extruder velocity are investigated.

1.3 Scope of the research

I. The consideration paste material is Dan Kwian clay in which a traditional material in north east of Thailand normally has been used to form traditional pottery.

II. The screw extrusion machine is a machine to construct clay model layer-by-layer based on the extrusion additive manufacturing. The workspace of this machine is a 200 mm. x 200 mm. x 300 mm. (width x length x height).

III. The length of clay filaments is 100 mm. and the width of clay filaments was measured at three positions of filament by using a digital microscope.

IV. To evaluate 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.

V. Independent variables are screw pitch (18, 24 mm.), nozzle diameter (5, 6, 7 mm.) and screw extruder velocity (14, 19, 24 mm/s)

VI. A response variable is a clay filament diameter.

1.4 Research procedure

The research procedure starts with Chapter I, which presented the background on the extrusion-based additive manufacturing techniques and identification of the problem. Then, the research objective and scope of the study were presented. Chapter II presented the theoretical extrusion-based system which focuses on this research. The applications of the material extrusion-based additive manufacturing and screw extrusion were reviewed. The comparison of the material extrusion techniques with the characteristic of feedstocks and the limitations were present in which the extrusion mechanisms were classified into three categories. In addition, the background on the clay material was present. Chapter III is composed of the clay printing machine configuration, material preparation, printing parameters and experiments. The experiment element was conducted with the identification a proper formular of clay material for the clay printing machine and the experiment of material deposition of the machine. Chapter IV presented the analysis of the experimental results. The main effects of the parameters on the width of extruded clay filament were identified. The linear model relating the width of clay filament to the main effects was presented. Finally, all the findings in this research were summarized and the recommendations of the research were pointed out in Chapter V. The research procedure is illustrated in Figure 1.7

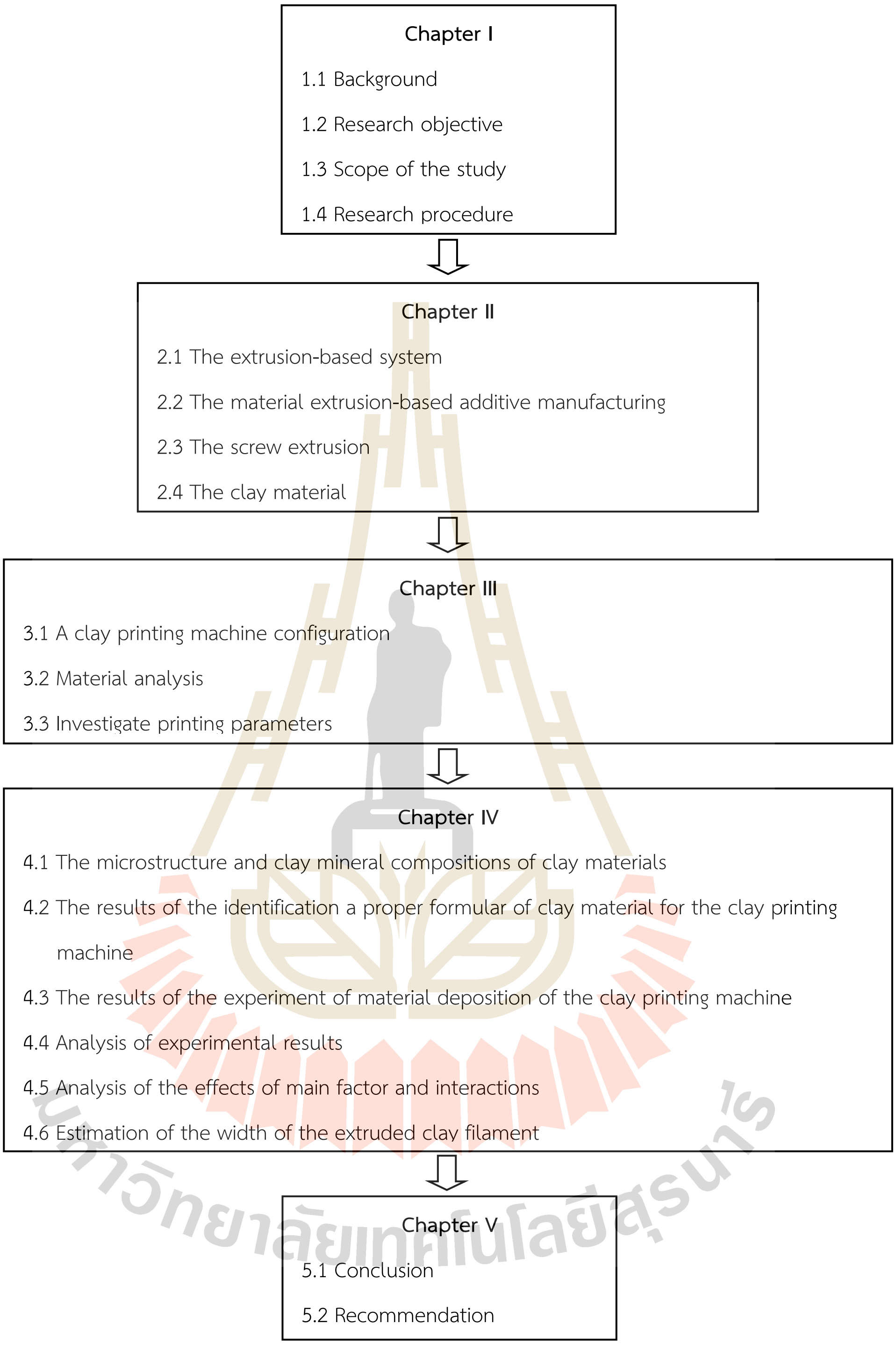


Figure 1.7 The research procedure

CHAPTER II

LITERLATURE REVIEW

2.1 The extrusion-based system

The extrusion-based additive manufacturing is a process that used extrusion to fabricate 3D models layer by layer. This process is developed based on the basic principle of the conventional polymer extrusion process. An extruder of the extrusion-based additive manufacturing is vertically mounted on the moving system different from the extruder of the conventional polymer extrusion process. In the extrusion process, feedstock that is contained in a reservoir is pushed out though a nozzle by applying the pressure. The characteristic of the extruded material is semi-liquid stage. So, it is able to join with previous layer before solidifying. The extrusion-based additive manufacturing processes have been developed and applied to many fields with difference materials. There are several techniques in the extrusion-based additive manufacturing processes such as fused deposition modeling (FDM), robocasting (RC), direct ink writing (DIW), freeze-form extrusion fabrication (FEF) and aqueous-based extrusion fabrication (ABEF). The extrusion mechanisms and the methods of the solidification are used to classify these techniques (Hu, Mikolajczyk, Pimenov and Gupta., 2021).

2.2 The material extrusion-based additive manufacturing (MEAM)

According to the International Organization for Standardization (ISO) and America Society for Testing and Materials (ASTM) 52900:2015, the material extrusion is defined as an additive manufacturing process in which material is extruded through a nozzle to form 3D models layer-by-layer on a platform. In AM processes, the MEAM processes are widely used due to an uncomplicated printing mechanism, variety of applications and low costs (Jiang et al., 2020).

The MEAM processes have been several applied to form 3D objects into many sectors such as food, ceramic and architecture. The MEAM processes can be classified into three categories based on the extrusion mechanism as show in Figure 2.1. Filament-based, plunger-based and screw-based extrusion have been used to extrude solid, liquid or viscosity materials, which will be described in this section.

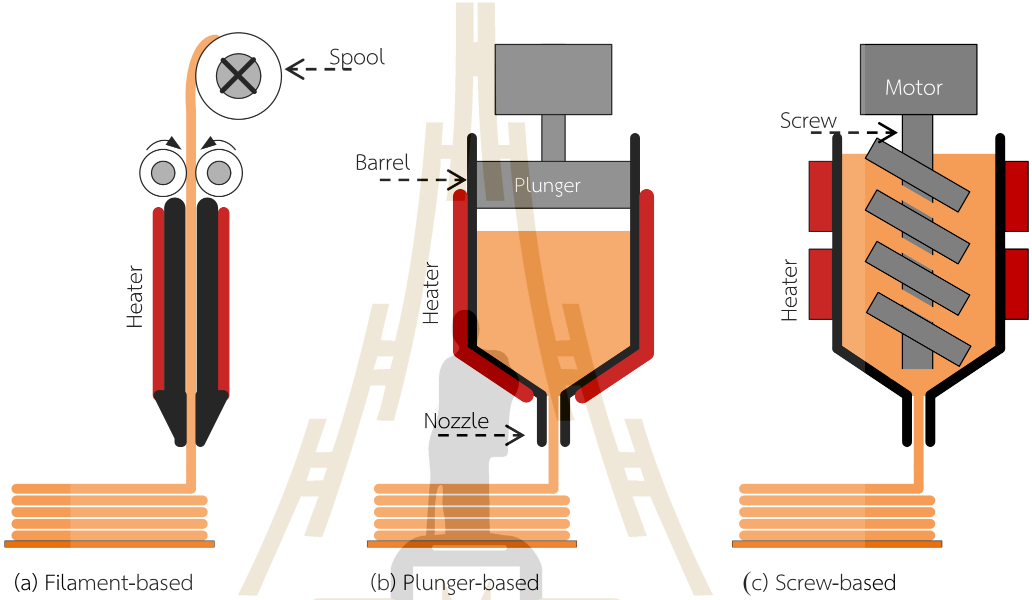


Figure 2.1 Three categories of the extrusion mechanism

2.2.1 Filament-based extrusion

Filament-based extrusion or fused deposition modeling (FDM) is one of the extrusion-based additive manufacturing techniques. Which is the most widely used for production variety plastic models. A schematic of this technique is shown in Figure 2.1 (a). The polymeric materials in form of a filament which are rolled in a spool in which it is heated to reach semi-liquid state and then extruded though a nozzle onto the platform for fabricating 3D model layer by layer. FDM process has been the most widely used to form several 3D models with a wide range of materials, size, complex geometries and low cost. Acrylonitrile butadiene styrene (ABS), poly actic Acid (PLA), polyamide (PA) and polycarbonate (PC) are commonly thermoplastics used for FDM processes (Calignano et al., 2017). There are the wide range of temperatures which is helpful for extruding. After extrusion, the extruded polymer is able to rapidly solidify so that the models can be mainland the shape (Zhang, Wang, Li J., Li X., and Cheng., 2020). Ceramics, metal, and variety combination of them have been using in fused deposition modeling process (Nurhudan, Supriadi, Whulanza and Saraih., 2021). However, this process has disadvantages of available materials in the form a filament, instable flow of low viscosity material and buckling of filament (Ngo, Kashani, Imblazano, Nguyen and Hui., 2018).

2.2.2 Plunger-based extrusion

Plunger-based extrusion, also referred to as syringe-based extrusion is one of the extrusion-based additive manufacturing techniques in which materials in form of liquid or soft-material are loaded into a barrel. Then, the material is extruded though a nozzle onto the platform by a linear plunger movement. The plunger is controlled by using a stepper motor. Therefore, the extrusion rate is controlled by adjusting of the speed motor. A schematic of this technique is shown in Figure 2.1 (b). In food printing, Plunger-based extrusion, also referred to as syringe-based extrusion has been widely applied in 3D food printing process (Sun, Zhou, Yan, Huang and Lin., 2018). Malon and Lipson (2007) introduced the Fab@Home model 1, which is an open-source 3D printer based on the syringe-based extrusion to form liquid food material. Lipton et al. (2010) used the Fab@home model 2 to print a prism shaped cookie. Also, the Netherlands Organisation for applied scientific research (TNO) has been developed the syringe-based extrusion process for a variety of foods (Van der linden, 2015). Kim, Eo and Cho (2018) used the piston type extrusion method to print various viscosity materials in order to find the optimal conditions of the machine. In additional, the plunger-based extrusion was used to form ceramic pastes (Li et al., 2017; Leu et al., 2012). On the other hand, there some materials which used the plunger-based extrusion with heater for extrusion process. The heaters are attached around a barrel to heat material into semi-liquid state. Then, the material is extruded though a nozzle onto the platform by a linear plunger movement. Amza, Zapciu and Popesce., (2017) presented the designed paste extruder hardware add-on for desktop 3D printer in which feedstock is heat and pressed through a nozzle by piston drive. After design the past extruder, 3D models were fabricated by using different paste materials such as silicone, acrylic and dental get. Singh G., Singh M., and Minz (2018) developed a piston extrusion system for formation of *peda* (milk-based sweet). The system consists of a cylindrical barrel, piston, die and temperature control. However, there are disadvantages of the plunger-based extrusion, such as dimensional inaccuracy, poor surface finish, a few of the molten material in the syringe and heavy extrusion mechanism because of material loaded.

2.2.3 Screw-based extrusion

In order to overcome the disadvantages of filament-based and plunger-based extrusion, screw-based extrusion technique has been developed. A schematic of this technique is shown in Figure 2.1 (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 layer by layer on the platform. In conventional polymer extrusion process, granular materials are fed into the hopper and conveyed into melting section by a screw extruder. Then, the granules are heated and become a molten material. Eventually, a molten material is pushed into the die to form the material into the design shape (Abeykoon, 2016). A conventional single-flighted screw extrusion, which is used in polymer extrusion process, is divided in the feeding section, compression section and metering section as shown in Figure 2.2. Nowadays, the conventional single screw extruder has been widely applying in the 3D forming processes. Netto et al., (2021) reviewed on the evolution of the extrusion additive manufacturing with screw-assisted. This review focused on the design system of the extruders that were used to feed the granular materials. In avoid the preparation of filament material process, the development of extrusion system in a commercial FMD technology was presented (Bellini, Shor and Guceri., 2005). The screw with constant pitch and depth was designed and assembled in the extrusion system of the commercial FMD technology as shown in Figure 2.3 (a). The granular ceramic was fed in the feeder tube and conveyed along the screw channel into the nozzle. The experiments were conducted to test the performant of the extrusion system. During the extrusion process, it was observed that when the size of granule less than 3 mm, the agglomeration of granules occurred in the feeder tube.

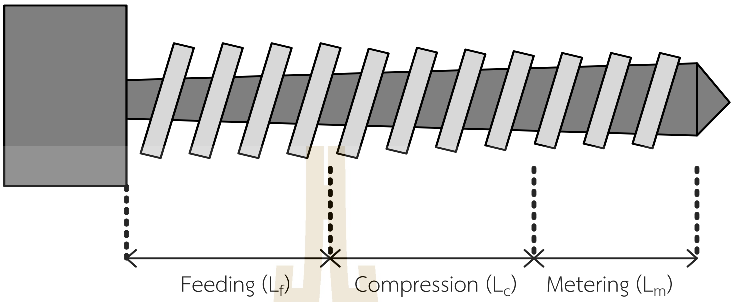


Figure 2.2 Schematic diagram of a conventional single-flighted screw extrusion

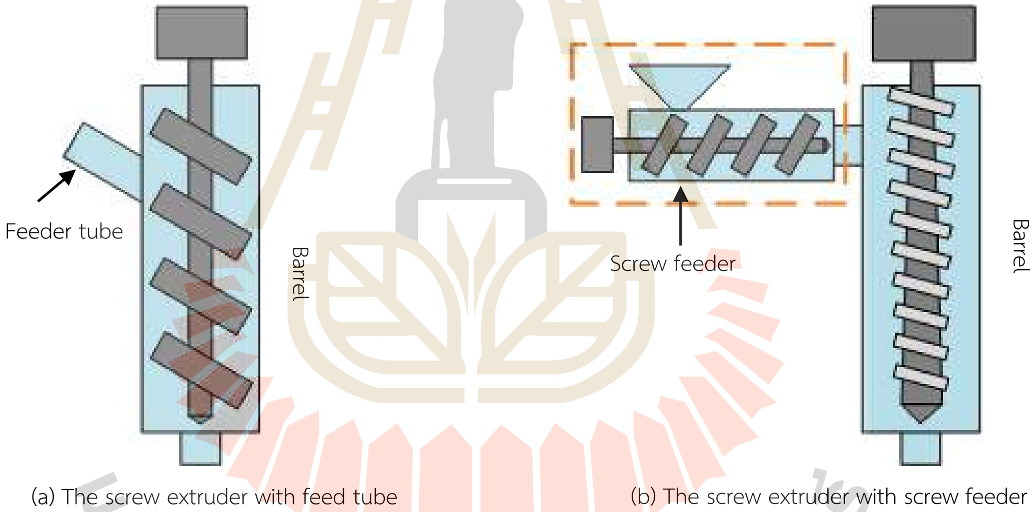


Figure 2.3 Schematic diagrams of the screw extruders

To avoid the feeding problem that mentioned, an automatic screw feeder as shown in Figure 2.3 (b) was developed for feeding polymeric pellets (Reddy B., Reddy N. and Ghosh., 2007). Moreover, a screw extruder with variable depth and pitch was design and assembled in the extrusion system in order to eliminate air entrapment. But, the feeder of the material was mounted on the barrel to avoid the compression of the material as shown in Figure 2.4 (a) (Silvera and Freitas., 2014). The screw with three sections was developed and assembled in the extrusion system of the FDM technology. The raw material in form a powder was used to extrude continuous filaments for investigation of the capacity of extrusion head. Kumart, Jain, tandon and Pandy., (2018) presented the screw extrusion-based material deposition tool which developed which consists of the screw, barrel, hopper, band heater, supporting frame and tool holder. According to literatures mentioned above, the reviews focus on the

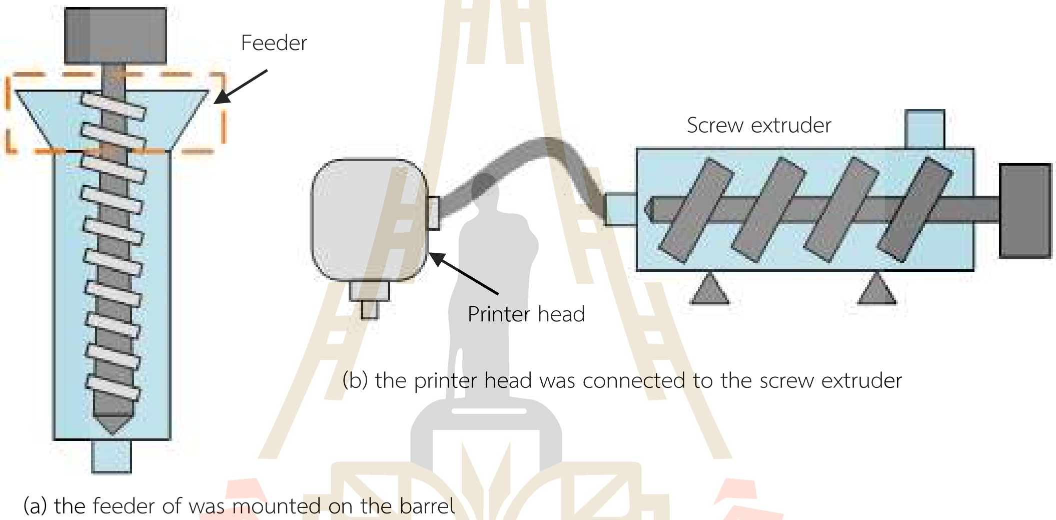


Figure 2.4 Schematic diagrams of the screw extruders

materials in form of granule which was used in the 3D printing process with screw-based extrusion. On the other hand, the screw-based extrusion has been widely applied into 3D food printing processes in which viscosity materials are extruded out of the nozzle on the platform to fabricate the designed 3D shape. Hao et al., (2010) presented the new chocolate additive layer manufacturing process (ChocALM). The ChocALM consists of the tempering chamber, delivery system of material, deposition head and the positioning system. The viscosities of chocolate were characterized. Line tests were used to study the effects of the extrusion rate and nozzle moving speed on the extruded chocolate geometry. Wang, Zhang, Bhandari and Yang., (2018) presented a new 3D food printing based on screw extrusion. Nozzle diameters, nozzle heights, nozzle movement speeds, extrusion rate and material properties of fish surimi gel are printing parameters, which were conduced to find the optimization of printing parameters. The experimental test was found that the 2.0 mm nozzle diameter, 5.0 mm nozzle height, 28 mm/s nozzle movement speed and 0.003 cm/s extrusion rate were optimal parameters to print 3D models with smooth surface and good geometry. Lemon juice gel was used to print 3D models by using the developed 3D food printing. An equation that shows the relationship between the nozzle diameter, the nozzle movement speed and the extrusion rate was purposed (Yang, Zhang and Bhandari., 2017). The equation is used to estimate the nozzle movement speed when the nozzle diameter and the extrusion rate were known. In addition, the material in form pastes can be used to form 3D models by using the screw-based extrusion concept. Hong et al., (2015) modified the FDM printer in which the printer head was connected to the screw extruder that was separated from the FDM printer structure as shown in Figure 2.4 (b). High viscosity Cu pastes were fed into the screw extruder and extruded to form 3D metal structures. As previously mentioned, the filament-based, plunger-based and screw-based extrusion are the MEAM techniques that have been widely applied to fabricate 3D models. Table 1 presents the comparison of the MEAM techniques that are used in 3D model processes, the characteristic of feedstock and the limitations of each technique.

Table 2.1 The comparison of the MEAM techniques with the characteristic of feedstocks and the limitations

Extrusion mechanisms	Description	Characteristic feedstocks	Limitations
Filament-based	Process in which the materials in form of a filament is heated to reach semi-liquid state and then extruded though a nozzle onto the platform.	Filaments of polymers, ceramics, metals, biomaterials and composite	Available materials in the form a filament, instable flow of low viscosity material and buckling of filament
Plunger-based	Process in which the materials in form of a semi-liquid or soft-material is extruded though a nozzle by a linear plunger movement.	Paste, High viscosity of materials such as jam, mayonnaise, peanut butter and ketchup Molten chocolate, milk-based sweet	Dimensional inaccuracy, poor surface finish, a few of the molten material in the syringe and heavy extrusion mechanism because of material loaded
Screw-based	Process in which the materials are extruded through a nozzle by the rotating of screw extruder	Granular of ABS, PLA, PCL and composites High viscosity metal paste, ceramic and clay /chocolate / lemon juice gel / fish surimi	Large structure, complex extrusion mechanism,

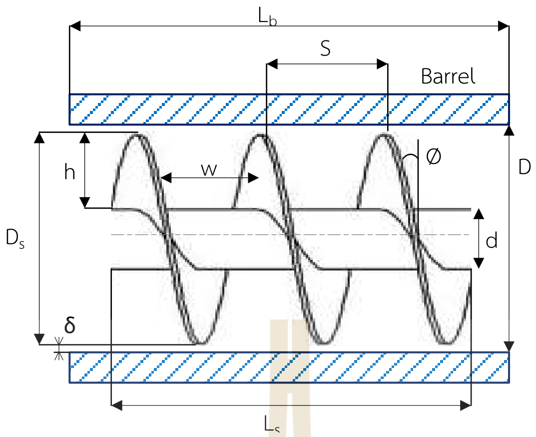


Figure 2.5 Schematic diagram of screw geometry

Table 2.2 Parameter for screw geometry

Parameter	Symbol	Dimension
Barrel length	L_b	mm
Screw length	L_s	mm
Barrel diameter	D	mm
External screw diameter	D_s	mm
Internal screw diameter	d	mm
Screw pitch	S	mm
Flight depth	h	mm
Chanel width	w	mm
Helix angle	Ø	o
Screw clearance	δ	mm

2.3 The screw extrusion

Previously literatures that were mentioned, highlighted the applications of the screw-based extrusion in 3D model processes. However, there are few literatures that studied on the design of the screw extrusion for 3D model process. A conventional single-flighted screw a shown in Figure 2.2, The screw is the key component of the screw extruder in which the viscosity material in the barrel is pushed along the screw channel through a nozzle by the pressure that is generated by the screw rotating. A diagram of screw geometry is shown in Figure 2.5 and parameters of screw geometer are summarized in Table 2.2. The conventional single-flighted screw extrusion is divided into 3 sections as the feeding, compression and metering. The function of feeding section is to convey solid material from the hopper to the compression section. In this section, flight depth is designed with constant depth and pitch. Which has a large depth when compared with another section in order to increase enough volume of material to convey into metering section. In the compression section, the flight depth constantly decreases along the length of the section in order to improve the compression, but still constant pitch. During this section, the solid material is melted to become molten material which is compressed to eliminate the entrained air. Then, the molten material is conveyed to metering section. The flight depth of the metering section is smaller depth than another section. In the metering section, the material is completely melted stage and homogenized which is extruded through the shaping die. The amount of the extruded directly relates to the screw length and screw diameter. Equation 2.1 is a ratio of the screw length and the external screw diameter (*L/D*) in which the screw length (*L*) divided by the external screw diameter (*D*).

$$L / D = \frac{\text{The screw length}}{\text{The external screw diameter}} \tag{2.1}$$

The *L/D* ratio is used to describe the relation between the screw length and the external screw diameter. Normally *L/D* ratio of screw is between 20:1 – 30:1. The high *L/D* ratio has a larger output than low *L/D* ratio (Wagner, Mount and Giles., 2014). Because characters and properties of the material used in the FDM process are similar to the material used in the plastic extrusion. Therefore, the conventional single-flighted screw that is used in the polymer extrusion process has been widely applying for vertical extruder in the FDM process. Valkenares et al., (2013) designed a screw extrusion based on the conventional single screw of plastic extrusion for 3D printing process. The *L/D* ratio was determined as 10:1 to reduce the time of material that stay in the extruder. A screw extrusion-based additive manufacturing was developed to print polyether-ether-ketone material (Tseng et al., 2017). The screw extrusion was designed with the *L/D* ratio as 20:1 (tola length screw = 280 mm, screw diameter = 14 mm and screw pitch = 14 mm).

2.4 The clay material

Ceramic is one of the most materials, used to fabricate 3D models in the extrusion-based additive manufacturing processes because of high mechanical strength, manufacturing scalability and low cost of raw material (Zocca, Colombo, Gomes and Gunster., 2015). The ceramic materials of the extrusion-based additive manufacturing processes are categorized in two forms as filament and paste. The ceramic in filament form is widely used in the FDM process. However, the process of the filament preparation becomes a limitation of this process. So, ceramic in paste form is a more flexible material. In this study, the paste is a mixture of clay and water, used to form pottery models. Generally, the solid component of a paste has a particle size in the range 0.1 – 100 μm (Benbow and Bidgater., 1993). Clay becomes soft and plastic when water is added. The plastic character is defined as the ability of clay material to be moulded without rupture when force is applied (Bergaya and Laaly., 2013). Kaolinite clay form Colombia with different water to clay ratio (w/c) between 0.57 -0.65 % was prepared and printed cylindrical models by using the DIW technique (Revelo and Colorado., 2015). The experimental results were found that w/c ratio in the 0.36 – 0.40 % produce printable models. The w/c ratio at 0.60 % showed the best result in term of the flow test and the surface finish. In 2019, Revelo and Colorado used the DIW technique to fabricate kaolinite clay with several ceramic additive powder. The experimental results were found that the w/c ratio at 0.70 % with fly ash as an additive powder were the best in term of mechanical properties and surface finishing.

In this study, 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 (Srilomsak, Pattanasiriwisawa, Somphon, Tanthanuch and Meethong., 2014). The main mineral compositions of Dan Kwian clay are quartz (45.7 wt%), kaolinite (42.3 wt%) and feldspar (5.6 wt%) (Poowancum and Horpibulsuk., 2015). Traditionally, ceramic and pottery products are formed by using paster mold or hand throwing. A general process of pottery forming is shown in Figure 1.4. 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. Then, the green body is dried and fired to temperatures of 900 – 1100 °C in kiln. Former design and low productivity are limitations of the pottery forming process by hand throwing. 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.

CHAPTER III

EXPERIMENTAL PROCEDURE

This chapter depicts the experimental work on a design of clay printing machine, an evaluation of clay materials and an experiment of capability material deposition. The process sequence of the experiment is organized as follow. A clay printing machine configuration was presented in section 3.1. In section 3.2, clay samples were analyzed to study microstructure and clay mineral compositions. Also, an appropriate formulation of clay material was identified. Experimental parameters were investigated and the design of experiment was presented in section 3.3.

3.1 A clay printing machine configuration

The clay printing machine has been developed based on the paste extrusion process, in which a machine constructs clay models layer-by-layer. The principle of this machine is the deposition of clay materials through a nozzle to form 3D models without mold and die. The clay printing machine was designed based on 3-axis Cartesian gantry positioning system which is controlled by stepper motors. The machine is controlled by an Arduino Mega 2560 R3 board with the Marlin firmware, which controls the screw velocity, nozzle movement speed, platform movement speed and other settings. The workspace of this machine is a 200 mm x 200 mm x 300 mm (width x length x height). The clay printing machine composes five major components as shown in Figure 3.1: (I) a material container for delivering system, (II) a screw extruder for extrusion, (III) a platform, (IV) movement system for moving a nozzle in X and Y directions, in which these components have been controlled by stepper motors via Computer Numerical Control (CNC) programming, and (V) a control panel.

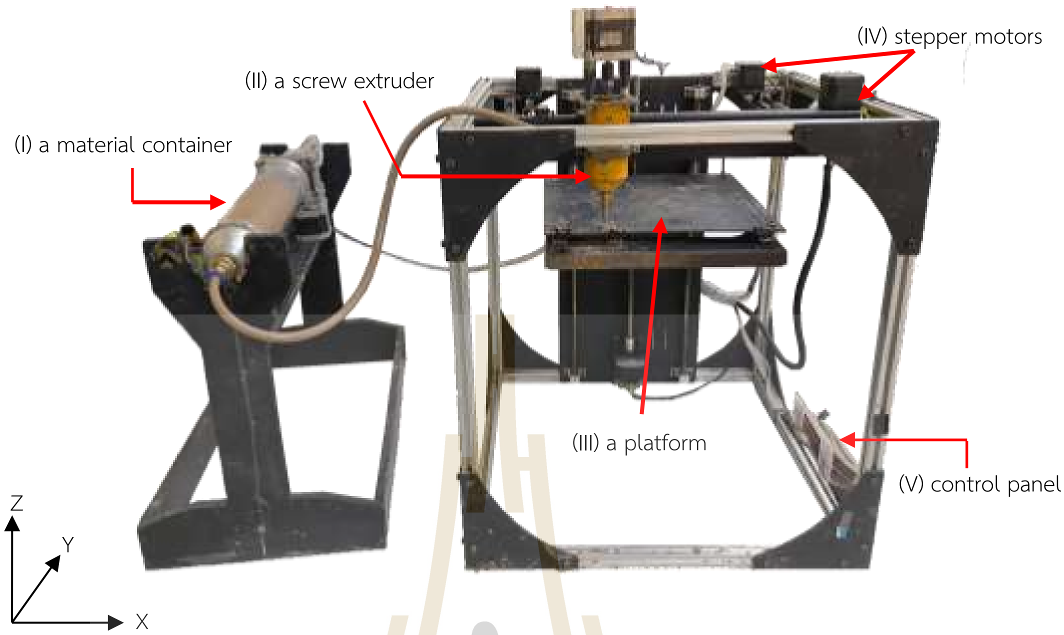


Figure 3.1 A clay printing machine based on the paste extrusion process

3.1.1 Machine specification

3.1.1.1 The material container and connector tube

The material container is fabricated from a plastic material. The capacity of material container is 1,000 milliliters (mL). The material container as shown in Figure 3.2 functions as a piston extruder, in which the clay material is extruded through a connector tube into a screw extruder by applying pressure. The material container connects with the screw extruder by male straight pneumatic fitting and plastic tube. The diameter of the tube is 10 mm. and the length is 650 mm. Geometric parameter valves of material container are shown in Table 3.1.

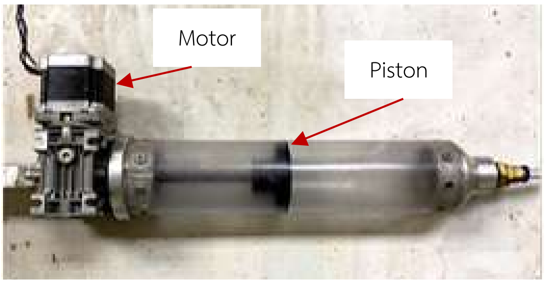


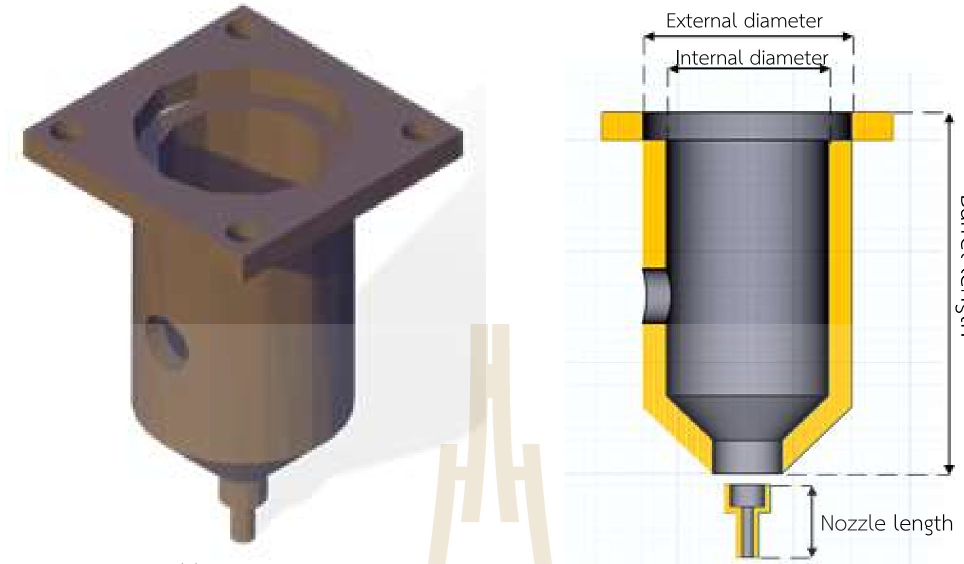
Figure 3.2 Diagram of the material container

Table 3.1 Geometric parameter valves of material container

Parameter	Value
Cylinder diameter (C_d)	75 mm
Cylinder length (C_l)	320 mm
Capacity	1,000 mL

3.1.1.2 The barrel extruder

The main components of screw extruder are the barrel, screw and nozzle as shown in Figure 3.3, while the platform moves up and down along the Z direction. The barrel of the extruder interfaces with a nozzle in which the varying diameter of the nozzle can be changed. The barrel is fabricated from metal material in which the geometry parameter values of the barrel are shown in Table 3.2.



(a) 3D model (b) Cross section view

Figure 3.3 3D diagram and cress section view of the screw extruder

Table 3.2 The geometry parameter values of the barrel

Parameter	Value
External diameter (B_d)	50 mm
Internal diameter (B_i)	38 mm
Barrel length (B_l)	108 mm
Nozzle length (N_l)	40 mm

3.1.1.3 The screw extrusion

The screw extruder of the clay printing machine was designed without the heating system, in which the main functions of the extruder are compression and transportation of the clay material through a nozzle. 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. In this research, the screw extruders were designed based on a principle of basic conveyor flight and pitch types. There are two screw types to apply for experiment. 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, which can be calculated using an equation 3.1 (Fruchtbaum J., 1988). This parameter was applied to control flow rate of extruded material. A diagram of the short pitch, single flight screw geometry is shown in Figure 3.4. Besides, the half pitch, single flight screw is used for handling fluid materials. This screw pitch is equal to 1/2 screw diameter, which can be calculated using an equation 3.2 (Fruchtbaum J., 1988). A diagram of the half pitch, single flight screw geometry is shown in Figure 3.5. the geometry parameter values of the screw extrusions are shown in Table 3.3. Actual representation of the single flight screws are shown in Figure 3.6.

$$\text{Screw pitch} = \frac{2}{3}\left(\text{Screw diameter}\right) \tag{3.1}$$

$$\text{Screw pitch} = \frac{1}{2}\left(\text{Screw diameter}\right) \tag{3.2}$$

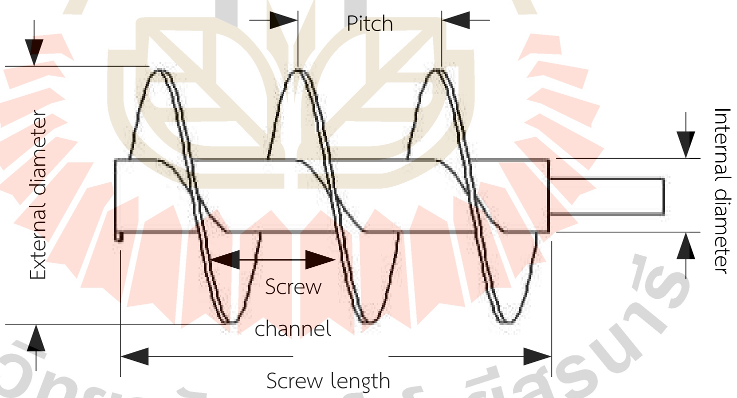


Figure 3.4 Schematic diagram of the shot pitch, single flight screw

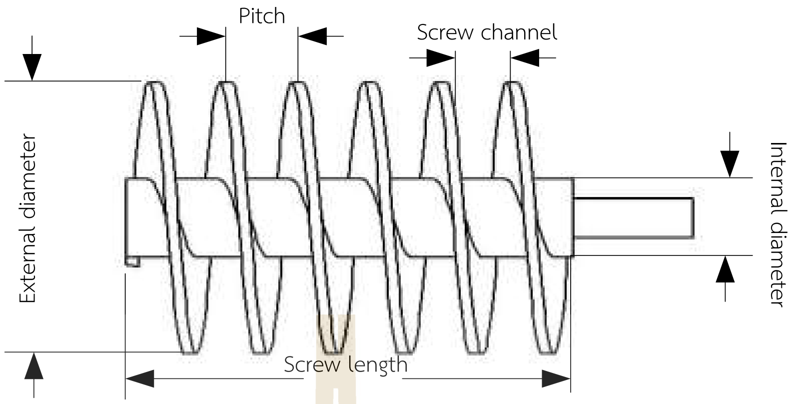


Figure 3.5 Schematic diagram of the half pitch, single flight screw

Table 3.3 The geometry parameter values of the screw extrusions

Parameter	The single flight screw	
	Short pitch,	Half pitch
External diameter (D)	36 mm	36 mm
Internal diameter (d)	16 mm	16 mm
Screw length (L_S)	75 mm	75 mm
Helix angle (Ø)	6°	6°
Pitch (P)	24 mm	18 mm
Screw channel (S_C)	20 mm	9 mm

(a) the shot pitch, single flight screw

(b) the half pitch, single flight screw

Figure 3.6 Actual representation of the single flight screws

3.1.2 The extrusion process of the clay printing machine

The process of clay model forming starts with fabrication of 3D models, in which the models are designed by using software model. Then, the 3D model is converted into STL file format that are sliced to be equal to a layer thickness into horizontal layers by an open-source slicer programming. The contours file is uploaded to the clay printing machine by universal serial bus (USB) port or memory card at the control panel port. Clay material is loaded into the material container. The screw velocity, nozzle movement speed and infill levels are the parameters setting, in which the clay printing machine is set up prior to the extrusion process. To start the extrusion process, the clay material is extruded through a connector tube into the screw extruder by applying pressure. The pressure is generated by controlling the position of the piston, which are controlled by a stepper motor. When the clay is pressed into the screw extruder. The clay is pushed and conveyed along the screw channel through a nozzle by the screw rotation. The screw is driven by a step motor, which is the key component of the extruder. The screw extruder moves along X-Y directions following contours data, in which the extruder is controlled by step motors via Computer

Numerical Control (CNC) programming. When a considering layer is complete for all contours. The platform is lowered (z direction) with a layer thickness and a new layer is fabricated. These two steps are repeated until the model is completely fabricated, in which the model is fabricated layer by layer on the platform. The process sequence of the clay printing machine is shown in Figure 3.7.

3.2 Materials analysis

3.2.1 Evaluation of clay materials

Representative clay samples of Dan kwian clay, Compound lampang clay and Ratchaburi red clay were prepared in form powder-based. Those clay samples were analyzed to study microstructure, clay minerals and mineral compositions which are suitable for the clay printing machine. The microstructures of the clay samples were analyzed using Scanning electron microscopy (SEM, Carl Zeiss AURIGA) method. X-ray diffraction (XRD, Burker D2 phaser) with CuK_a radiation (λ = 15406 Å) scanning between 0° and 70° was used to analyze the mineral compositions of the clay samples.

3.2.2 Identify an appropriate formulation of material for the clay printing machine

Generally, the Dan kwian clay of Dan kwian pottery is mixed between Dan kwian clay and Dan kwian sand in proportion 2:1. Which has small particle sizes, high viscosity, high plasticity and a lot of iron oxide in the clay. The original Dan kwian clay cannot be used in the clay printing machine because of high viscosity. Therefore, the Dan kwian clay with water 1,000 mL and different proportion sand mixed were prepared in order to decrease the viscosity. The experimental clay formulations are shown in Table 3.4.

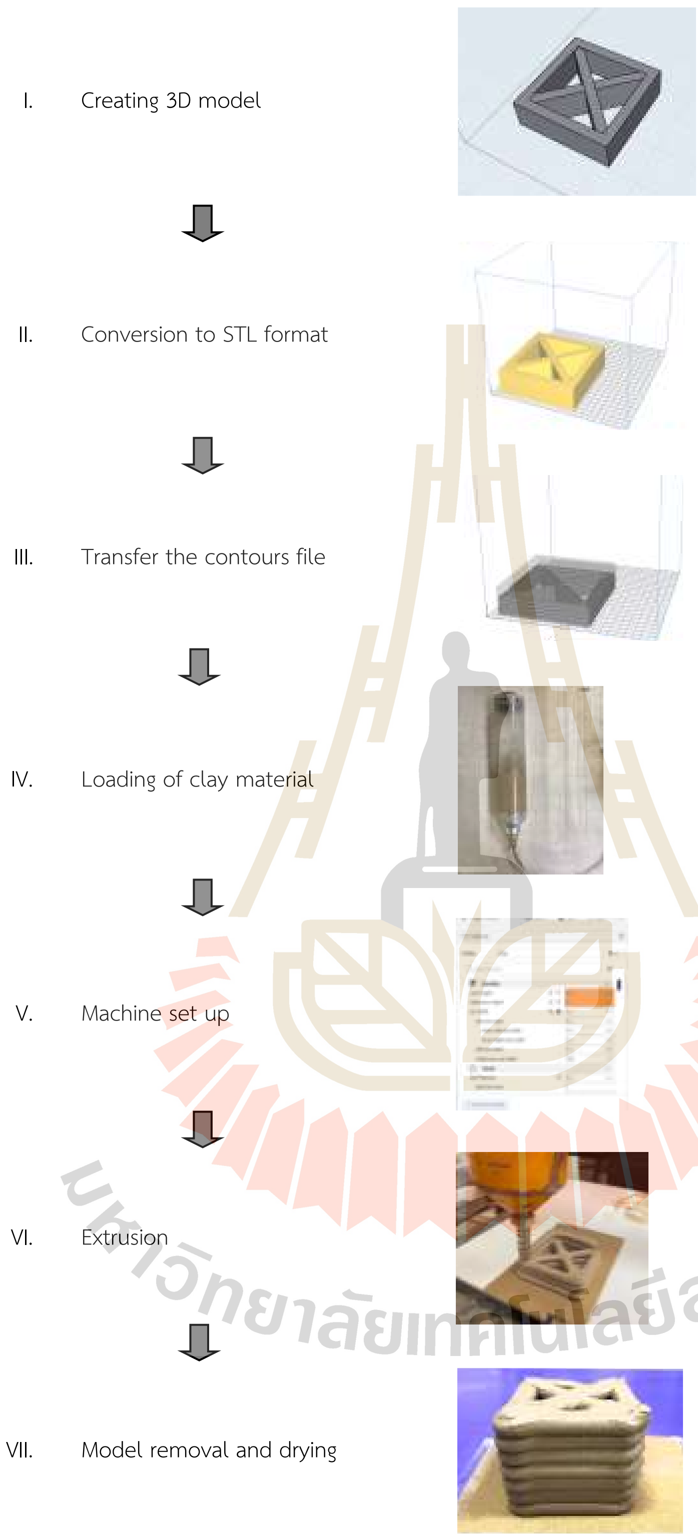


Figure 3.7 The paste extrusion process based on the clay printing machine

Table 3.4 Three formulations of the experimental clay

Formulation	Proportion	Dan kwian clay (kg)	Sand (kg)	Water (mL)
1	1:0	1	0	1,000
2	1:0.5	1	0.5	1,000
3	1:1	1	1	1,000

3.2.3 Experiment design for identifying a formulation of clay material

A single factor experiment technique was used to analyze and define a suitable clay formulation for the clay printing machine. The experimental clay is a factor in which there are three formulations. Each formulation was experimented to print five extruded clay filaments in which each length of clay filament is 100 mm. A response variable is a width of extruded clay filament that was measured. While fixed variables are nozzle diameter, screw velocity and screw pitch. The factor levels, fixed variables and a response variable are shown in Table 3.5. The Analysis of variance (ANOVA) technique was used to analyze the effects of the factor level in the width of the extruded clay filament.

Table 3.5 The printing parameters for the material testing

Factor	Level
Clay formulations	1 (1:0:1) 2 (1:0.5:1) 3 (1:1:1)
Printing parameter	**Value**
Nozzle diameter	6 mm
Screw extruder velocity	14 mm/s
Screw pitch	18 mm
Response variable	**Value**
The width of extruded clay filament	measurement

3.2.3.1 The analysis of variance

There are three levels of a single factor. Factor A denotes the clay formulations in which *i* th is level of factor A (*i* = 1, 2, 3). Y_{ij} denotes the *j*th response (replication) taken under factor level *i* (*j* = 1, 2, 3, 4, 5). Therefore, there are 15 (3 x 5) total responses, are shown in Table 3.6. The responses are randomly selected one by one to arrange the order of the experiment. Therefore, this experiment is a completely randomized design in which the order of the experiments is shown Table 3.7. The effect model that describes the response from this experiment as shown in equation 3.3

$$Y_{ij} = \mu + \tau_i + \varepsilon_{ij} \tag{3.3}$$

Where μ is the overall mean, and τ_i is a *i*th level effect. ε_{ij} is a random experimental error. After finishing a treatment experiment, the widths of each extruded clay filament were measured by using an ImageJ program. The measurements were taken at three positions (1, 2 and 3) as shown in Figure 3.8 in which the mean value of the three widths was calculated and recorded in the Table 3.7.

Table 3.6 The arrangement of the single factor for material testing

Treatment (level)	Responses				
1	Y_{11}	Y_{12}	Y_{13}	Y_{14}	Y_{15}
2	Y_{21}	Y_{22}	Y_{23}	Y_{24}	Y_{25}
3	Y_{31}	Y_{32}	Y_{33}	Y_{34}	Y_{35}

Table 3. 7 The order of the single factor experiment

Order	Level	Response	Order	Level	Response
1	1	Y_{13}	9	1	Y_{11}
2	3	Y_{33}	10	2	Y_{22}
3	1	Y_{12}	11	1	Y_{14}
4	3	Y_{31}	12	2	Y_{24}
5	2	Y_{23}	13	3	Y_{35}
6	2	Y_{25}	14	3	Y_{32}
7	1	Y_{15}	15	3	Y_{34}
8	2	Y_{21}			

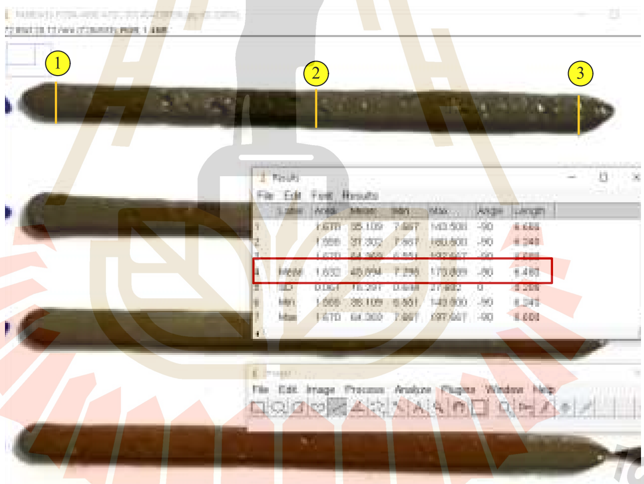


Figure 3.8 An example of measurement by ImageJ program

3.2.3.2 Hypothesis testing

By the equation 3.3, the effect of the factor levels has an influence on the responses. Therefore, the hypothesis testing was used to analyze the influence of the factor level on the responses. The testing focuses on the influences of each level factor A (τ_i) effect or not effect to the width of the extruded clay filament. The null hypothesis (H_0) and alternative hypothesis (H_1) of the factor levels were presented in equations 3.4. The P-value approach was used to report the results of a hypothesis test. The P-value is the probability that is a smallest level of significance in which the null hypothesis was or was not rejected. In this experiment, the smallest level of significance is equal to 0.05 in which the null hypothesis was rejected with the P-value is less than 0.05 (P-value < 0.05). The values of the *P*-value were calculated from a statistical test. The ANOVA technique was processed with Minitab software (Minitab® 18.1: © 2017 Minitab, Inc. All rights reserved). Differences of $p < 0.05$ were determined to be significant.

$$H_0 : \tau_1 = \tau_2 = \tau_3 = 0$$
$$H_1 : \tau_i \neq 0 \text{ for at least one } i \quad (3.4)$$

3.3 Investigate printing parameters

3.3.1 Printing parameters

In the extrusion process, the clay paste is pushed along the screw channel and extruded through a nozzle by rotation of the screw. The screw is controlled by a step motor via CNC programming. Therefore, the characters and the amount of the extruded clay filament depend on the screw character and the velocity of the rotation of the screw. In order to control the diameters and the characters of clay filament, screw extruder velocity, screw pitch and nozzle diameter were set as the printing parameters. The printing parameters are listed in Table 3.8.

Table 3.8 The printing parameters

Printing parameter	Unit
Nozzle diameter (N)	mm
Screw extruder velocity (V_s)	mm/s
Screw pitch (P)	mm

3.3.2 Experiment design for investigate printing parameters of the clay printing machine

Design of Experiment (DoE) method was applied to study the effect of printing parameters (factors) on the width of the extruded clay filament (response variable). Therefore, factorial design technique is efficient for this experiment in which all combination of the levels of the factors are investigated for each replication of the experiment. The ANOVA technique was processed with Minitab software (Minitab® 18.1: © 2017 Minitab, Inc. All rights reserved). Differences of P-value < 0.05 were determined to be significant. To investigate a capability material extrusion of the clay printing machine, the printing parameters that effect on the extrusion and their levels were determined in order to control the width of the extruded clay filament. There are three levels of the screw extruder velocity, three levels of the nozzle diameter and two levels of the screw pitch. A response variable is a width of extruded clay filament that was measured. While fixed variables are screw length, internal diameter of screw, external diameter of screw and helix angle. The printing parameter, fixed variable and response variable are shown in Table 3.9. By a factorial design, factor A denotes the screw pitch, factor B denotes the nozzle diameter and factor C denotes the screw extruder velocity. While $Y_{ijk,t}$ denotes the response that are effected from factors level i, j, k and their interactions. When *i* th is level of factor A (*i* = 1, 2), *j* th is level of factor B (*j* = 1, 2, 3), *k* th level is factor C (*k* = 1, 2,3) and *t* th is replication (*t* = 1, 2, ..., *n*). The effects model of the response in this a factorial experiment shows as an equation 3.5.

$$Y_{ijk,t} = \mu + \tau_i + \beta_j + \gamma_k + (\tau\beta)_{ij} + (\tau\gamma)_{ik} + (\beta\gamma)_{jk} + (\tau\beta\gamma)_{ijk} + \varepsilon_{ijk} \qquad (3.5)$$

$$\mu = \frac{\Sigma_{i=1}^{2}\Sigma_{j=1}^{3}\Sigma_{k=1}^{3}Y_{ijk,t}}{N} \qquad (3.6)$$

Where μ is the overall mean effect as shown in an equation 3.6. *N* is total the observed responses. τ_i is the effect of the *i*th level factor A. β_j is the effect of the *j*th level factor B. γ_k is the effect of the *k*th level factor C. $(\tau\beta)_{ij}$ is the effect of the interaction between τ_i and β_j. $(\tau\gamma)_{ik}$ is the effect of the interaction between τ_i and γ_k

. $(\beta\gamma)_{jk}$ is the effect of the interaction between β_j and γ_k . $(\tau\beta\gamma)_{ijk}$ is the effect of the interaction between τ_i, β_j and γ_k . ε_{ijk} is an error term.

Table 3.9 The experimental parameters

Printing parameters	Factor	Level	Value
Screw pitch (P)	A_i ; i = 1, 2	2	18, 24 mm
Nozzle diameter (N)	B_j ; j = 1, 2, 3	3	5, 6, 7 mm
Screw extruder velocity (V_S)	C_k ; k = 1, 2, 3	3	14, 19, 24 mm/s
Fixed variable	**Value**		**Unit**
External diameter (D)	36		mm
Internal diameter (d)	16		mm
Screw length (L_s)	75		mm
Helix angle (Ø)	6°		degree
Response variable		**Value**	
The width of extruded clay filament ($Y_{ijk,t}$)		measurement	

3.3.3 The experiments planning

In this research, there are three levels of factor A, three levels of factor B, two levels of factor C. So, there are 18 (3 x 3 x 2) treatment combinations. Each treatment composed of 20 extruded clay filaments (replication) in which each length of extruded clay filament is 100 mm. Therefore, there are 360 (3 x 3 x 2 x 20) total responses. Factorial design experiments are shown in Table 3.10. The responses are randomly selected one by one to arrange the order of the experiment. Therefore, this factorial design is a completely randomized design in which the order of the experiments is shown Table 3.11.

Table 3.10 The arrangement of a factorial design for extrusion testing

Factor A_i	Factor B_j	Factor C_k	Response
A_1	B_1	C_1	$Y_{111,1}, Y_{111,2}, Y_{111,3}, \ldots, Y_{1111,8}, Y_{1111,9}, Y_{111,20}$
		C_2	$Y_{112,21}, Y_{112,22}, Y_{112,23}, \ldots, Y_{112,38}, Y_{112,39}, Y_{112,40}$
		C_3	$Y_{113,41}, Y_{113,42}, Y_{113,43}, \ldots, Y_{113,58}, Y_{113,59}, Y_{113,60}$
	B_2	C_1	$Y_{121,61}, \ldots, \ldots, \ldots, \ldots, \ldots, Y_{121,80}$
		C_2	$Y_{122,81}, \ldots, \ldots, \ldots, \ldots, \ldots, Y_{122,100}$
		C_3	$Y_{123,101}, \ldots, \ldots, \ldots, \ldots, \ldots, Y_{123,120}$
	B_3	C_1	…, …, …, …, …, …, …
		C_2	…, …, …, …, …, …, …
		C_3	…, …, …, …, …, …, …
A_2	B_1	C_1	…, …, …, …, …, …, …
		C_2	…, …, …, …, …, …, …
		C_3	…, …, …, …, …, …, …
	B_2	C_1	…, …, …, …, …, …, …
		C_2	…, …, …, …, …, …, …
		C_3	…, …, …, …, …, …, …
	B_3	C_1	$Y_{231,301}, \ldots, \ldots, \ldots, \ldots, \ldots, Y_{231,320}$
		C_2	$Y_{232,321}, \ldots, \ldots, \ldots, \ldots, \ldots, Y_{232,340}$
		C_3	$Y_{233,341}, \ldots, \ldots, \ldots, \ldots, \ldots, Y_{233,360}$

Table 3.11 The order of the factorial design experiments

Order	Screw pitch (A_i)	Nozzle diameter (B_j)	Screw extruder velocity (C_k)	Response
1	24	6	19	$Y_{222,1}$
2	24	6	19	$Y_{222,2}$
3	24	6	19	$Y_{222,3}$
.	.	.	.	.
.	.	.	.	.
20	24	6	19	$Y_{222,20}$
21	18	6	19	$Y_{122,21}$
22	18	6	19	$Y_{122,22}$
.	.	.	.	.
.	.	.	.	.
40	18	6	19	$Y_{122,40}$
41	24	5	14	$Y_{211,41}$
42	24	5	14	$Y_{211,42}$
.	.	.	.	.
.	.	.	.	.
60	24	5	14	$Y_{211,60}$
61	24	7	24	$Y_{233,61}$
62	24	7	24	$Y_{233,62}$
.	.	.	.	.
.	.	.	.	.
80	24	7	24	$Y_{233,80}$
81	18	5	19	$Y_{112,81}$
82	18	5	19	$Y_{112,82}$
.	.	.	.	.
.	.	.	.	.
100	18	5	19	$Y_{112,100}$

Table 3.11 (Continued)

Order	Screw pitch (A_i)	Nozzle diameter (B_j)	Screw extruder velocity (C_k)	Response
101	24	7	14	$Y_{221,101}$
102	24	7	14	$Y_{221,102}$
103	24	7	14	$Y_{221,103}$
.	.	.	.	.
.	.	.	.	.
120	24	7	14	$Y_{221,120}$
121	18	5	24	$Y_{113,121}$
122	18	5	24	$Y_{113,122}$
.	.	.	.	.
.	.	.	.	.
140	18	5	24	$Y_{113,140}$
141	24	5	19	$Y_{213,141}$
142	24	5	19	$Y_{213,142}$
.	.	.	.	.
.	.	.	.	.
160	24	5	19	$Y_{213,160}$
161	18	6	14	$Y_{121,161}$
162	18	6	14	$Y_{121,162}$
.	.	.	.	.
.	.	.	.	.
180	18	6	14	$Y_{121,180}$
181	24	6	24	$Y_{223,181}$
182	24	6	24	$Y_{223,182}$
.	.	.	.	.
.	.	.	.	.
200	24	6	24	$Y_{223,200}$

Table 3.11 (Continued)

Order	Screw pitch (A_i)	Nozzle diameter (B_j)	Screw extruder velocity (C_k)	Response
201	18	7	19	$Y_{132,201}$
202	18	7	19	$Y_{132,202}$
203	18	7	19	$Y_{132,203}$
.	.	.	.	.
.	.	.	.	.
220	18	7	19	$Y_{132,220}$
221	24	7	14	$Y_{231,221}$
222	24	7	14	$Y_{231,222}$
.	.	.	.	.
.	.	.	.	.
240	24	7	14	$Y_{231,240}$
241	24	5	24	$Y_{213,241}$
242	24	5	24	$Y_{213,242}$
.	.	.	.	.
.	.	.	.	.
260	24	5	24	$Y_{213,260}$
261	24	6	14	$Y_{221,261}$
262	24	6	14	$Y_{221,262}$
.	.	.	.	.
.	.	.	.	.
280	24	6	14	$Y_{221,280}$
281	18	7	14	$Y_{131,281}$
282	18	7	14	$Y_{131,282}$
.	.	.	.	.
.	.	.	.	.
300	18	7	14	$Y_{131,300}$

Table 3.11 (Continued)

Order	Screw pitch (A_i)	Nozzle diameter (B_j)	Screw extruder velocity (C_k)	Response
301	24	5	14	$Y_{211,301}$
302	24	5	14	$Y_{211,302}$
303	24	5	14	$Y_{211,303}$
.	.	.	.	.
.	.	.	.	.
320	24	5	14	$Y_{211,320}$
321	18	6	24	$Y_{123,321}$
322	18	6	24	$Y_{123,322}$
.	.	.	.	.
.	.	.	.	.
340	18	6	24	$Y_{123,340}$
341	18	7	24	$Y_{133,341}$
342	18	7	24	$Y_{133,342}$
.	.	.	.	.
.	.	.	.	.
360	18	7	24	$Y_{133,360}$

3.3.4 Hypothesis testing

By the equation 3.4, the effect of the factors and their interactions have an influence on the responses. Therefore, the hypothesis testing was used to analyze the influence of the factors and their interactions on the responses. The null hypothesis (H_0) and alternative hypothesis (H_1) of the factors and their interactions in this research were presented in equations 3.7 – 3.13. In this research, the P-value approach was used to report the results of a hypothesis test. The P-value is the probability that is a smallest level of significance in which the null hypothesis was or was not rejected. In this experiment, the smallest level of significance is equal to 0.05 in which the null hypothesis was rejected with the P-value is less than 0.05 (P-value $<$ 0.05). The values of the P-value were calculated from a statistical test. The screw pitch (factor A_i), nozzle diameter (factor B_j) and screw extruder velocity (factor C_k) are the printing parameters, were studied in the hypothesis testing. For the screw pitch (factor

A_i), the influences of each level factor A (τ_i) effect or not effect to the width of the extruded clay filament. The statement of the null hypothesis and alternative hypothesis are shown as equation 3.7.

$$H_0 : \tau_1 = \tau_2 = 0$$
$$H_1 : \tau_i \neq 0 \text{ for at least one } i \tag{3.7}$$

For the nozzle diameter (factor B_j), the influences of each level factor B (β_j) effect or not effect to the extruded clay filament diameter. The statement of the null hypothesis and alternative hypothesis are shown as equation 3.8.

$$H_0 : \beta_1 = \beta_2 = \beta_3 = 0$$
$$H_1 : \beta_j \neq 0 \text{ for at least one } j \tag{3.8}$$

For the screw extruder velocity (factor C_k), the influences of each level factor C (γ_k) effect or not effect to the width of the extruded clay filament. The statement of the null hypothesis and alternative hypothesis are shown as equation 3.9.

$$H_0 : \gamma_1 = \gamma_2 = \gamma_3 = 0$$
$$H_1 : \gamma_k \neq 0 \text{ for at least one } k \tag{3.9}$$

For two-factor interaction effects of interaction AB, the influences of each treatment interactions between τ_i and β_j effect or not effect to the width of the extruded clay filament. The statement of the null hypothesis and alternative hypothesis are shown as equation 3.10.

$$H_0 : (\tau\beta)_{11} = (\tau\beta)_{12} = \ldots = (\tau\beta)_{23} = 0$$
$$H_1 : (\tau\beta)_{ij} \neq 0 \text{ for at least one} \tag{3.10}$$

For two-factor interaction effects of interaction AC, the influences of each treatment interactions between τ_i and γ_k effect or not effect to the width of the extruded clay filament. The statement of the null hypothesis and alternative hypothesis are shown as equation 3.11.

$$H_0 : (\tau\gamma)_{11} = (\tau\gamma)_{12} = \ldots = (\tau\lambda)_{23} = 0$$
$$H_1 : (\tau\gamma)_{ik} \neq 0 \text{ for at least one} \tag{3.11}$$

For factor B and C treatment interactions, the influences of each treatment interactions between β_j and γ_k effect or not effect to the width of the extruded clay filament. The statement of the null hypothesis and alternative hypothesis are shown as equation 3.12.

$$H_0 : (\beta\gamma)_{11} = (\beta\gamma)_{12} = \ldots = (\beta\gamma)_{33} = 0$$
$$H_1 : (\beta\gamma)_{jk} \neq 0 \text{ for at least one} \tag{3.12}$$

For thee-factor interaction effects of interaction ABC, the influences of each treatment interactions between τ_i, β_j and γ_k effect or not effect to the width of the extruded clay filament. The statement of the null hypothesis and alternative hypothesis are shown as equation 3.13. In general, the interaction ABC component has no practical interpretation, which is not analyzed in this experiment.

$$H_0 : (\tau\beta\gamma)_{111} = (\tau\beta\gamma)_{112} = \ldots = (\tau\beta\gamma)_{233} = 0$$
$$H_1 : (\tau\beta\gamma)_{ijk} \neq 0 \text{ for at least one} \tag{3.13}$$

3.3.5 Extrusion tests

To investigate a capability material extrusion of the clay printing machine, a straight-line printing test was designed to analyze the characters and appearances of the extruded clay filaments. The movement and extrusion system of the clay printing machine have been controlled by step motors which are controlled via CNC programming. So, this programming controls the functions of the machine using G-Code generated by a computer. The G-Code was used to generate the straight-line with the printing parameters as shown in Figure 3.9. A G1 command is a movement of the nozzle following a straight line in the X and Y axis direction with the moving speed (F) along the axis. E code is an extrusion command.

```
G21 ; set units to millimeters
M107
M104 S25 ; set temperature
G28 ; home all axes
G1 Z2 F720 ; lift nozzle
|
G90 ; use absolute coordinates
G92 E0
M82 ; use absolute distances for extrusion
G1 F720 X10 Y80
G92 X0 Y0
G1 Z5

G1 F720 X10 Y0
G1 F135 Y100 E30
G1 Y150 Z10
G92 E0

G1 F720 Z5 X30
G1 Y0 Z5
G1 F135 Y100 E30
G1 Y150 Z10
G92 E0
```

Figure 3.9 An example of G-code generated by a computer

In this the factorial design, there are 18 treatment combinations. Each treatment composed of 20 extruded clay filaments (replication) in which each length of extruded clay filament is 100 mm. While the distance between platform and nozzle were also equal to the nozzle diameter as shown in Figure 3.10. After finishing a treatment experiment, the widths of each extruded clay filament were measured by using an ImageJ program. The measurements were taken at three positions (1, 2 and 3) as shown in Figure 3.8 in which the mean value of the three widths was calculated and recorded in the Table 3.11. After complete experiment, the ANOVA technique was used to analyze the effects of the factors and their interactions.

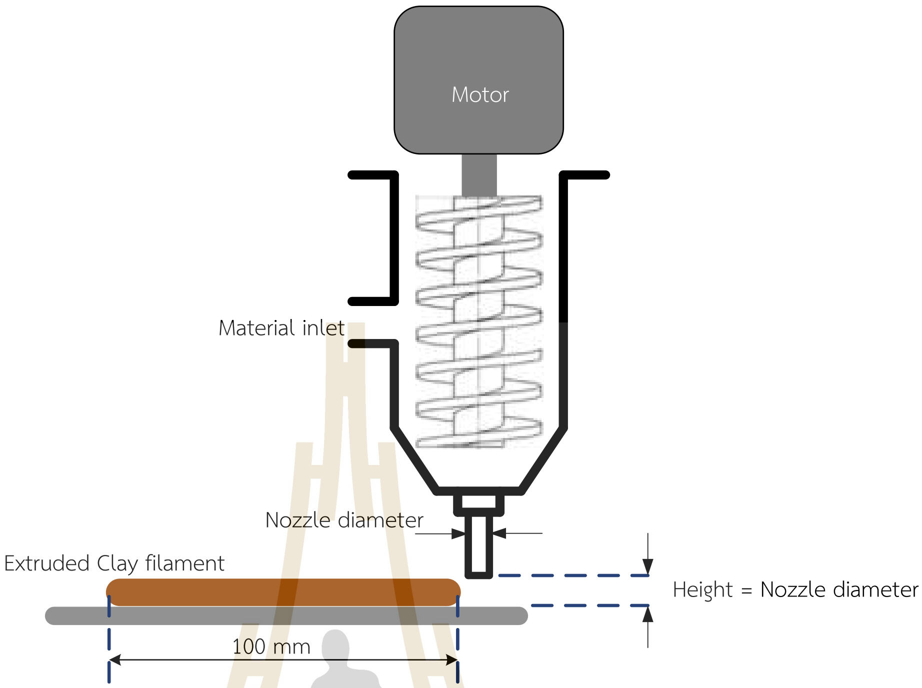


Figure 3.10 A diagram of experimental extrusion

In Chapter III, the clay printing machine was developed based on the paste extrusion process, in which the main functions of the screw extruder are compression and conveyance of the clay material through a nozzle. Three formulations of the clay material were present to identify a proper formulation for the clay printing machine. A single factor experiment technique was used to analyze and define a proper clay formulation for the machine. Then, the printing parameters were investigated to analyze the effects of the parameters on the extruded clay filament by the ANOVA technique. The analysis of the experimental results was described in Chapter IV.

CHAPTER IV

EXPERIMENTAL RESULTS AND DISSCUSION

This chapter display the microstructure and clay mineral compositions of clay samples. The experimental results of the identification a proper formular of clay material for the clay printing machine and the experiment of material deposition of the clay printing machine were presented. The experimental results were analyzed to identify a proper formulation, which was used to extrude in the clay printing machine. The results of the experiment of material deposition were analyzed to investigate the effects of the printing parameters and their interactions by the ANOVA technique. Then, the hypotheses were tested and the linear model relating the width of clay filament to the main effects was presented.

4.1 The microstructure and clay mineral compositions of clay materials

4.1.1 The microstructure of clay materials

Scanning electron microscopy (SEM) image of the Dan kwian clay is presented in Figure 4.1. Microstructure of the Dan kwian clay shows the typical mix of rounded and flakey particles. SEM image of the Compound lampang clay is presented in Figure 4.2 and SEM image of the Ratchaburi red clay is presented in Figure 4.3. Microstructure of the Compound lampang clay and the Ratchaburi red clay shown the typical laminar structure of flakey particles. The rounded geometry of particle shape has the lowest restriction in terms of anchoring sides limiting the flow through the printing nozzle (Carlos and Henry., 2019). Which is suitable to flow through the nozzle, when compared to other particle shapes.

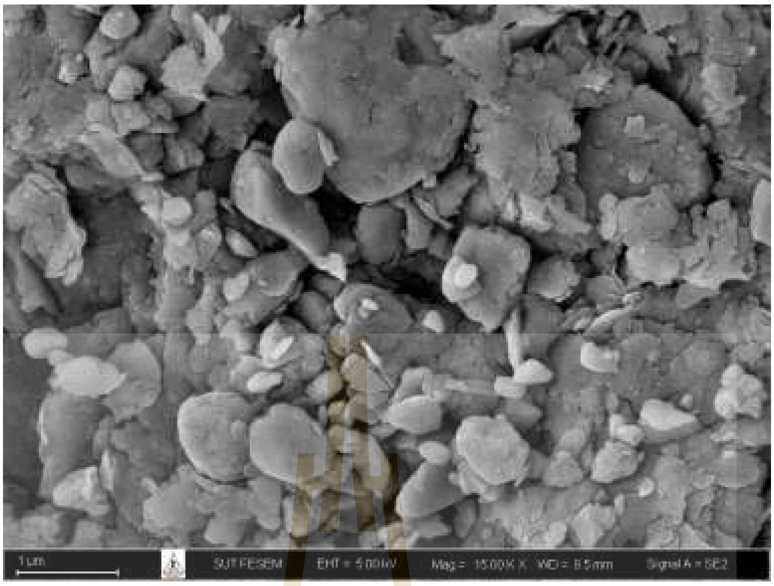


Figure 4.1 The SEM image of the Dan kwian clay

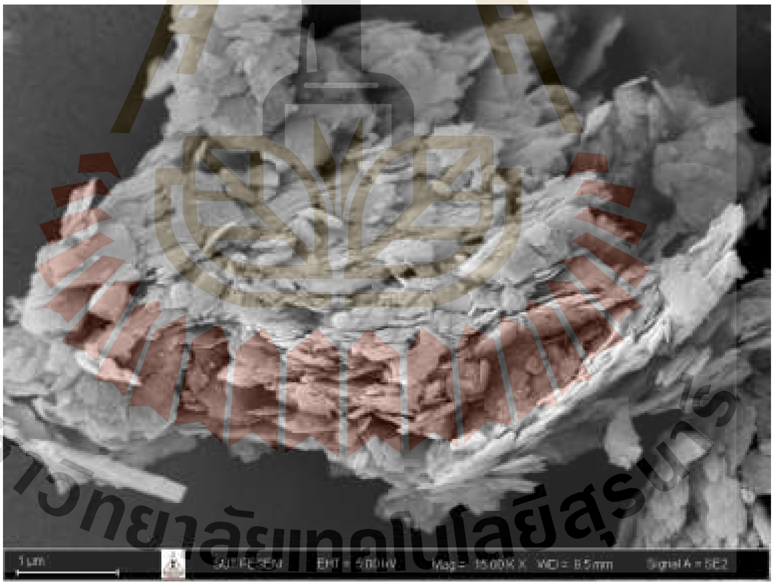


Figure 4.2 The SEM image of the Compound lampang clay

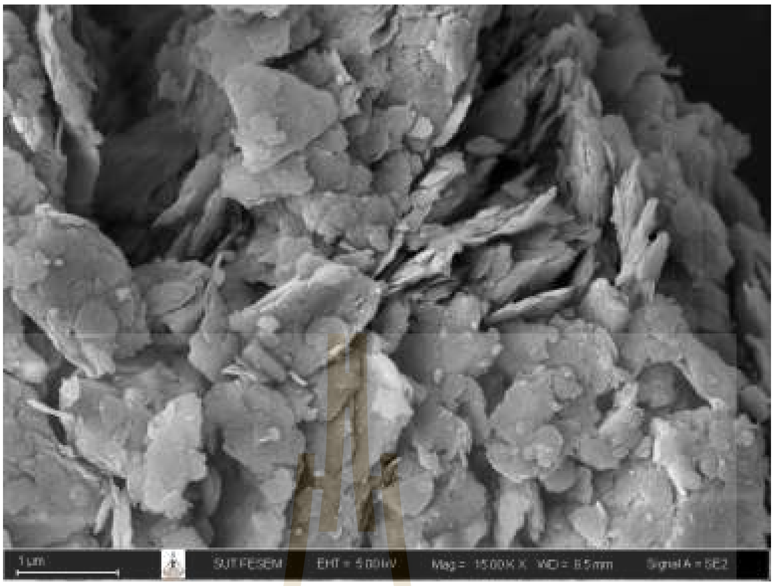


Figure 4.3 The SEM image of the Ratchaburi red clay

4.1.2 The mineral compositions of clay materials

The mineral compositions of the clay materials were analyzed by the X-ray diffraction (XRD) method. The XRD diffractograms of the clay samples are presented in Figure 4.5. Quartz (SiO_2) and kaolinite ($Si_2Al_2O_5(OH)_4$) were detected in all clay samples in which quartz is the main mineral composition. The kaolinite and illite ($K_yAl_4(Si_{8-y}Al_y)O_{20}(OH)_4$, $1 < y < 1.5$) are the minor mineral compositions, which were detected in the Ratchaburi red clay and the Compound lampang clay as shown in Figure 4.5 (a) and (b). Especially, Compound lampang clay has higher intensity peak of the kaolinite than the Ratchaburi red clay and the Dan kwian clay. The XRD diffractogram of the Dan kwian clay is presented in Figure 4.5 (c) in which the quartz and the kaolinite were detected. The Dan kwian clay has higher intensity peak of the quartz than the Ratchaburi red clay and the Compound lampang clay. The quartz crystal does not expand when clay is added to water. The kaolinite also does not absorb water and expands when clay is wet. The structure of kaolinite is fixed due to hydrogen bounding in which there is no expansion between the layers and low swelling (Kumari and Mohan., 2021). Therefore, clay models that were formed by the Dan kwian clay are able to stable shape than other clay because of the high quartz and the kaolinite component. On the other hand, the illite has a structural layer in which it expands when the clay is added to water. Which can be swelling by water molecules or cation infiltration (Li et al., 2021). The illite structure is an oxygen-oxygen linkage that causes higher space between layers than a hydrogen bonding of kaolinite structure (Mana, Hanafiah, and Chowdhury., 2018).

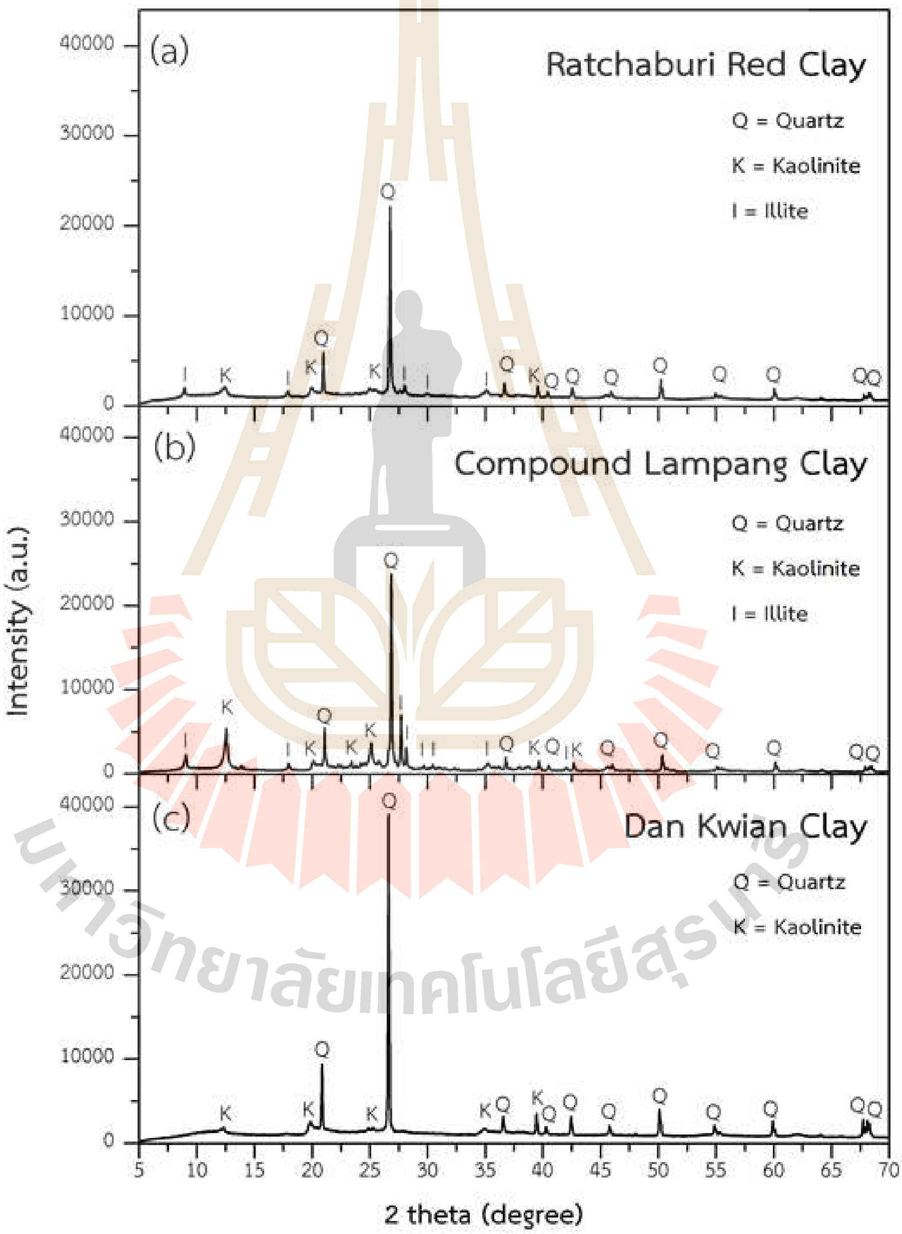


Figure 4.4 The XRD diffractograms of the clay samples : (a) Ratchaburi red clay, (b) Compound lampang clay, and (c) Dan kwian clay

4.2 The results of the identification a proper formulation of clay material for the clay printing machine

To identify a proper formulation of clay material for the clay printing machine. the results of this experiment are shown in Table 4.1, which are the width of the extruded clay filament. The extruded clay filaments are shown in Figure 4.1, were observed that the lines of the extruded clay filament with the formulation 1 (1:0) led to discontinuous lines as shown in Figure 4.5 (a). The lines of the extruded clay filament with the formulation 3 (1:1) led to large width and shown wavy character as shown in Figure 4.5 (c). While the lines of the extruded clay filament with the formulation 2 (1:0.5) demonstrate smooth and complete characters as shown in Figure 4.5 (b).

Table 4.1 The widths of extruded clay filament with different clay formulations

Treatment (level)	Responses				
1	5.455	5.000	5.707	5.598	5.156
2	6.326	6.210	6.204	6.253	6.338
3	7.846	7.897	8.103	7.667	7.526

(a) Line test of extruded clay filament with formulation 1 (1:0:1)

(b) Line test of extruded clay filament with formulation 2 (1:0.5:1)

(c) Line test of extruded clay filament with formulation 3 (1:1:1)

Figure 4.5 The results of the line test

4.2.1 Analysis of variance for the width of extruded clay filament

The ANOVA technique was processed with Minitab software in order to investigate the factor effect. The result of the ANOVA for the widths of extruded clay filament is summarized in Table 4.2. In this experiment, the smallest level of significance is equal to 0.05 in which the null hypothesis was rejected with the P-value is less than 0.05 (P-value < 0.05). The result of the ANOVA was found that P-value = 0.000 which less than 0.05. Therefore, the result of a hypothesis test is the null hypothesis (H_0) in equation 4.1 that was rejected at the 0.05 level of significance. That means the different clay formulations affect the mean width of extruded clay firmament. To check of the normality assumption, a normal probability plot of the residuals was used to investigate the normality assumption. The normal probability plot of the residuals is shown in Figure 4.6 in which the residuals distribute nearly the straight line. That implies this plot is normal. In addition, the plot of the residuals versus the fitted values presents structureless pattern as shown in Figure 4.7. A plot of the residuals versus observation order is shown in Figure 4.8. The residuals distribute in positive and negative residuals in which that implies this plot is an independence assumption.

$$\begin{aligned} &H_0 : \tau_1 = \tau_2 = \tau_3 = 0 \\ &H_1 : \tau_i \neq 0 \text{ for at least one } i \end{aligned} \tag{4.1}$$

Table 4.2 Analysis of variance for the widths of extruded clay filament

Source of variation	Degree of freedom	Sum of squares	Mean square	F-value	P-value
Level	2	15.0582	7.52909	159.53	0.000
Error	12	0.5663	0.04719		
Total	14	15.6245			

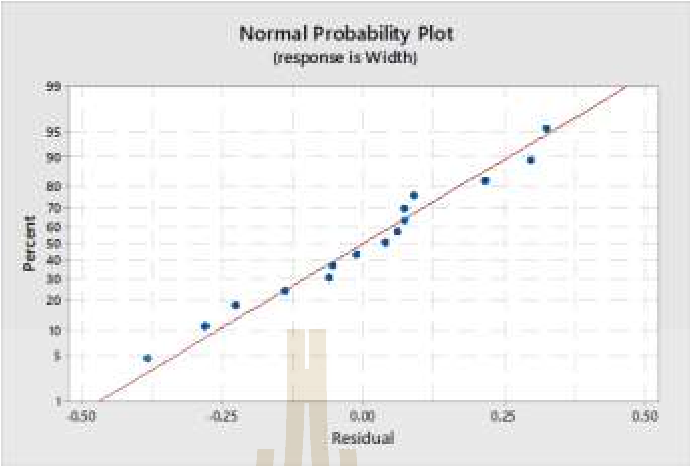


Figure 4.6 The normal probability plot of the residuals

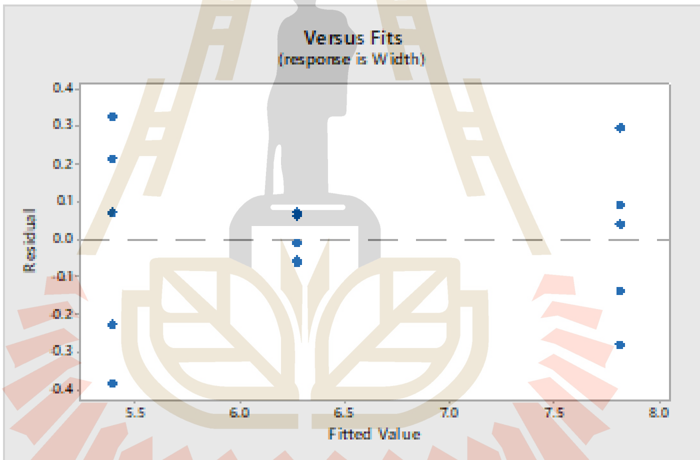


Figure 4.7 The plot of the residuals versus the fitted values

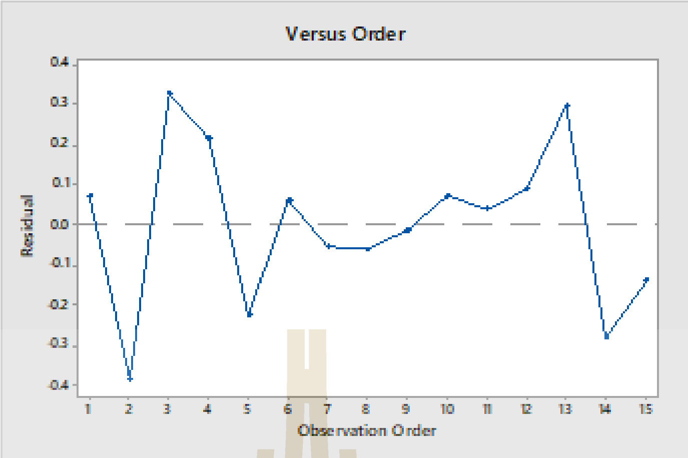


Figure 4.8 The plot of the residuals versus observation order

Figure 4.9 presents a plot of the main effect which has a positive effect. The mean width at each level was shown. In the preliminary experiment, the expected width of extruded clay filaments is equaled to the nozzle diameter (6 mm). The mean width at level 2 is 6.2662 mm which is close to the expected value. In addition, the extruded clay filament with this formulation demonstrates smooth and complete characters as shown in Figure 4.1 (b). Therefore, the clay formulation 1:0.5 (level 2) was a suitable formulation that was used to extrude in the clay printing machine.

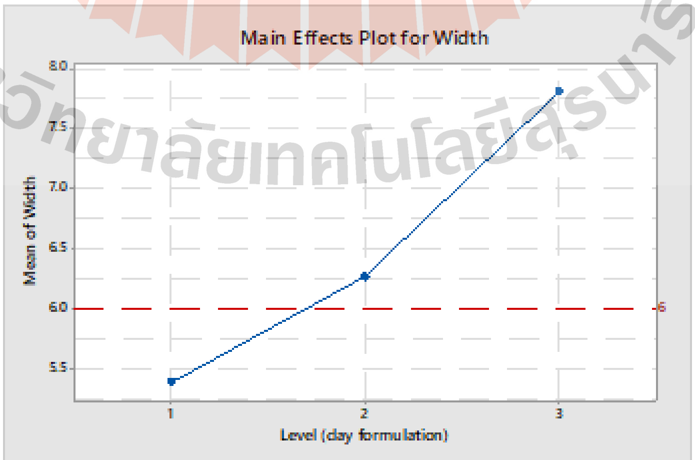


Figure 4.9 The main effects plot

4.3 The results of the experiment of material deposition of the clay printing machine

To develop a capability material deposition of the clay printing machine, the experiment of material extrusion of the machine was conducted. The screw pitch (P), nozzle diameter (N) and screw extruder velocity (V_s) are the printing parameters that affect the characters of the extruded clay filament. The results of this experiment are shown in Table 4.3, which are the width of the extruded clay filament. Experimental examples of the extruded clay filament for 18 mm screw pitch with different nozzle diameter and screw extruder velocity were shown in Figure 4.10. While experimental examples of the extruded clay filament for 24 mm screw pitch with different nozzle diameter and screw extruder velocity were shown in Figure 4.11.

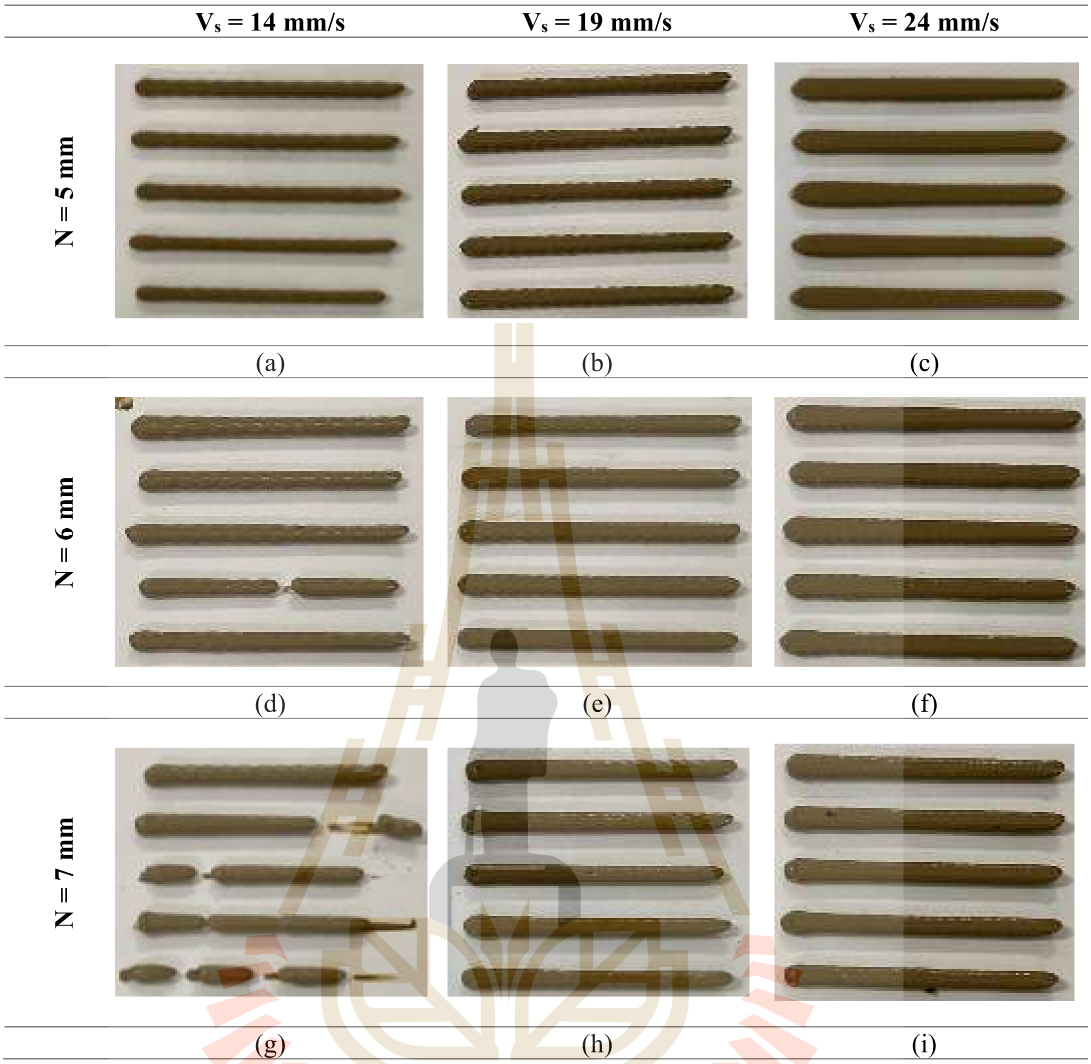


Figure 4.10 Examples of the extruded clay filament with 18 mm screw pitch

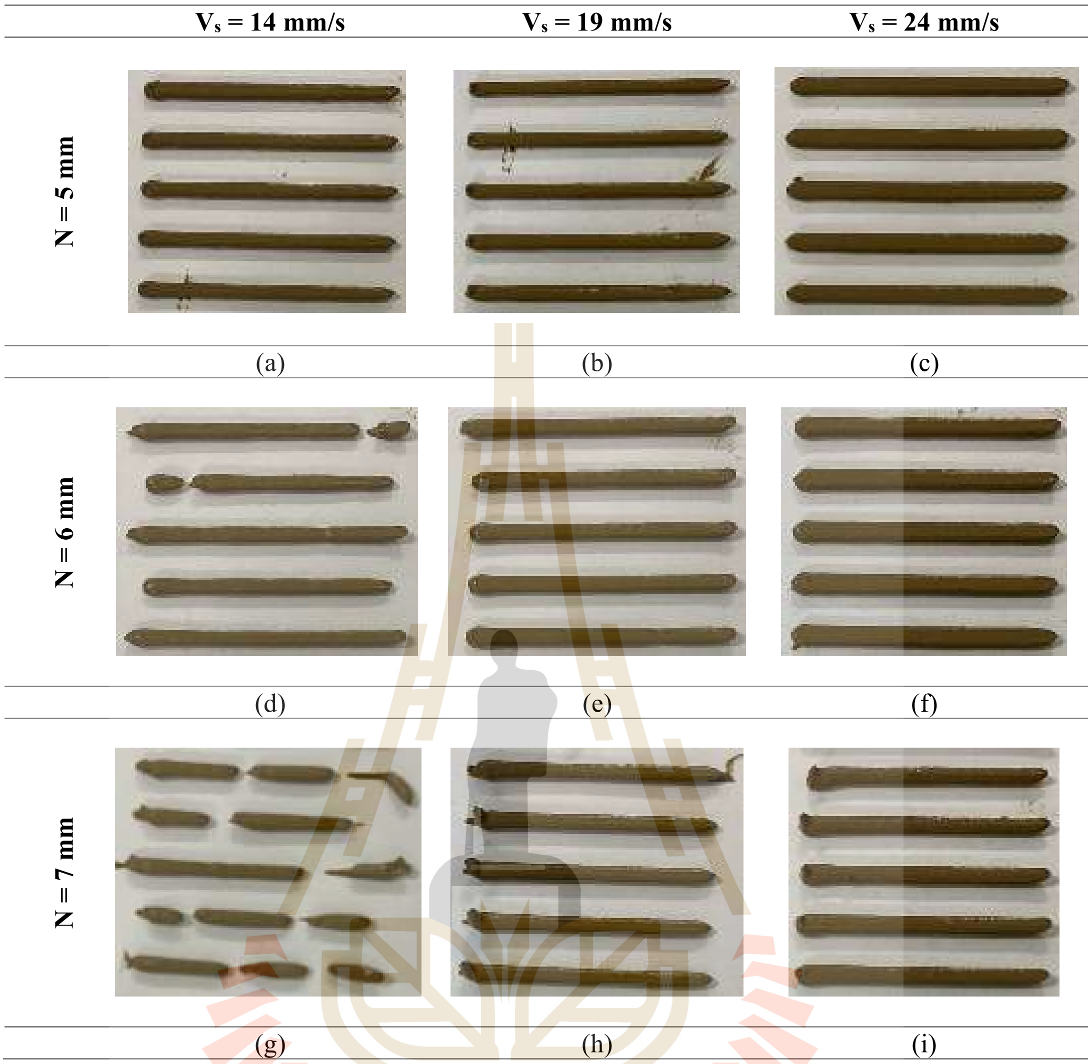


Figure 4.11 Examples of the extruded clay filament with 24 mm screw pitch

Table 4.3 The widths of extruded clay filament with printing parameters

Factor A_i	Factor B_j	Factor C_k	Response									
18 mm	5 mm	14 mm/s	6.071	5.749	5.887	5.841	5.535	5.795	5.780	5.474	6.101	6.025
		19 mm/s	7.080	7.064	6.820	6.774	6.835	6.449	6.407	5.964	6.315	6.682
		24 mm/s	7.065	7.523	7.554	7.431	7.309	8.242	7.752	8.028	8.249	8.333
	6 mm	14 mm/s	5.481	5.511	5.390	5.766	5.721	5.571	5.450	5.826	6.036	5.766
		19 mm/s	7.012	7.102	7.267	7.282	7.342	7.237	7.282	7.012	7.207	6.947
		24 mm/s	7.177	6.697	6.727	6.697	7.072	6.306	6.847	7.042	7.087	6.787
	7 mm	14 mm/s	6.116	5.703	5.385	5.706	5.428	5.581	6.053	6.300	5.430	5.444
		19 mm/s	6.957	6.499	6.315	6.621	6.086	6.333	6.451	6.162	6.330	5.951
		24 mm/s	7.217	7.080	7.248	7.263	7.294	7.691	7.202	7.569	7.504	6.927
24 mm	5 mm	14 mm/s	4.404	4.725	4.734	4.633	5.122	4.755	5.138	4.847	4.432	5.002
		19 mm/s	5.979	5.353	6.005	6.040	5.753	6.239	5.795	5.687	5.413	5.750
		24 mm/s	6.147	7.248	6.518	6.790	6.713	6.682	6.820	7.280	7.004	6.270
	6 mm	14 mm/s	5.886	6.441	6.547	6.607	6.622	6.592	6.547	6.381	6.246	6.066
		19 mm/s	6.441	6.231	6.622	7.132	6.547	6.712	6.832	6.366	6.592	6.622
		24 mm/s	7.252	7.207	7.417	7.342	7.177	7.974	7.808	7.688	7.703	7.985
	7 mm	14 mm/s	5.979	5.871	6.086	6.269	5.749	5.826	5.658	5.703	5.994	6.131
		19 mm/s	6.315	6.483	6.272	6.242	6.437	6.560	6.346	6.407	6.346	6.502
		24 mm/s	6.682	7.034	7.110	7.125	7.141	7.156	7.202	7.263	7.355	7.125

Table 4.3 (Continued)

Factor A_i	Factor B_j	Factor C_k	Response									
18 mm	5 mm	14 mm/s	5.765	5.963	5.841	6.184	6.070	5.627	5.612	5.336	5.551	5.581
		19 mm/s	7.018	6.911	6.774	6.942	7.003	7.171	6.330	6.850	6.667	6.667
		24 mm/s	8.028	8.257	8.180	7.783	8.058	8.119	8.103	8.149	8.058	8.043
	6 mm	14 mm/s	5.856	5.706	5.499	5.841	5.751	5.676	5.856	5.631	5.976	5.931
		19 mm/s	7.027	6.967	7.057	7.402	7.192	6.982	7.132	7.297	7.462	7.613
		24 mm/s	7.102	7.147	7.012	6.847	7.327	6.907	6.877	7.658	6.967	6.742
	7 mm	14 mm/s	5.749	5.994	5.747	6.069	5.550	6.009	5.795	5.792	5.810	5.536
		19 mm/s	6.697	6.483	6.055	6.132	6.590	6.483	6.483	6.132	6.315	6.636
		24 mm/s	7.294	7.218	7.263	6.957	7.752	7.615	7.284	7.171	7.447	6.942
24 mm	5 mm	14 mm/s	4.482	4.805	4.664	4.710	4.588	4.771	4.890	4.756	4.603	4.541
		19 mm/s	6.133	5.903	6.056	5.961	6.744	6.852	6.346	6.254	5.658	5.673
		24 mm/s	5.811	5.904	7.168	7.356	6.458	7.002	7.141	6.438	7.157	6.698
	6 mm	14 mm/s	5.991	6.426	6.216	6.126	6.396	6.487	6.456	5.991	6.081	6.006
		19 mm/s	6.306	6.532	6.967	7.012	7.252	7.372	7.132	7.132	6.907	6.922
		24 mm/s	8.183	7.447	7.958	7.568	7.312	8.018	7.793	7.988	7.808	8.093
	7 mm	14 mm/s	5.780	5.474	5.703	5.887	5.826	5.948	6.196	5.780	5.902	5.979
		19 mm/s	6.285	6.318	6.743	6.743	6.682	6.437	6.682	6.361	6.453	6.743
		24 mm/s	7.447	7.569	7.340	7.416	7.263	7.401	7.569	7.370	6.713	6.988

4.4 Analysis of experimental results

The ANOVA technique was processed with Minitab software in order to investigate the effect of the factors and their interactions. The result of the ANOVA for the widths of extruded clay filament is summarized in Table 4.4.

Table 4.4 Analysis of variance for the widths of extruded clay filament

Source of variation	Degree of freedom	Sum of squares	Mean square	F-value	P-value
Model	13	210.529	16.1945	161.24	0.000
Linear	5	171.695	34.3389	341.89	0.000
Screw pitch	1	4.176	4.1755	41.57	0.000
Nozzle diameter	2	12.480	6.2401	62.13	0.000
Screw extruder Velocity	2	155.039	77.5194	771.80	0.000
2-Way Interactions	8	38.834	4.8543	48.33	0.000
Screw pitch* Nozzle diameter	2	28.760	14.3800	143.17	0.000
Screw pitch* Screw extruder Velocity	2	1.033	0.5165	5.14	0.006
Nozzle diameter * Screw extruder Velocity	4	9.041	2.2603	22.50	0.000
Error	346	34.752	0.1004		
Lack-of-Fit	4	8.044	2.0109	25.75	0.000
Pure Error	342	26.708	0.0781		
Total	359	245.281			

In this experiment, the smallest level of significance is equal to 0.05 in which the null hypothesis was rejected with the P-value is less than 0.05 (P-value < 0.05). The result of the ANOVA was found that P-values of the factors and their interactions less than 0.05. Therefore, the results of the hypothesis tests are the null hypothesis

(H_0) of the factors and their interactions was rejected at the 0.05 level of significance. The experiment can conclude as:

I. The effects of significant factors

- The influence of the screw pitch (τ_i) effects to the width of the extruded clay filament.
- The influence of the nozzle diameter (β_j) effects to the width of the extruded clay filament.
- The influence of the screw extruder velocity (γ_k) effects to the width of the extruded clay filament.

II. The effects of significant interactions

- The influence of the interaction between the screw pitch and the nozzle diameter $(\tau\beta)_{ij}$ effects to the width of the extruded clay filament.
- The influence of the interaction between the screw pitch and screw extruder velocity $(\tau\gamma)_{ik}$ effects to the width of the extruded clay filament.
- The influence of the interaction between the nozzle diameter and screw extruder velocity $(\beta\gamma)_{jk}$ effects to the width of the extruded clay filament.

To check of the normality assumption, a normal probability plot of the residuals was used to investigate the normality assumption. The normal probability plot of the residuals is shown in Figure 4.12 in which the residuals were plotted close to a straight line. That implies this plot is normal. In addition, the plot of the residuals versus the fitted values presents structureless pattern as shown in Figure 4.13. A plot of the residuals versus observation order is shown in Figure 4.14. The residuals distribute in positive and negative residuals in which that implies this plot is an independent assumption.

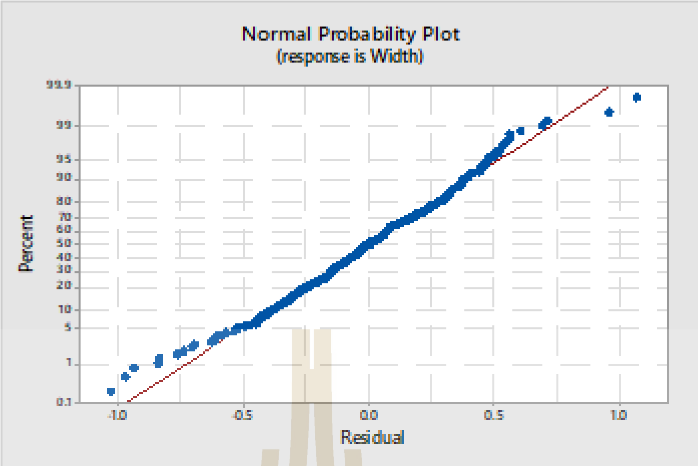


Figure 4.12 The normal probability plot of the residuals

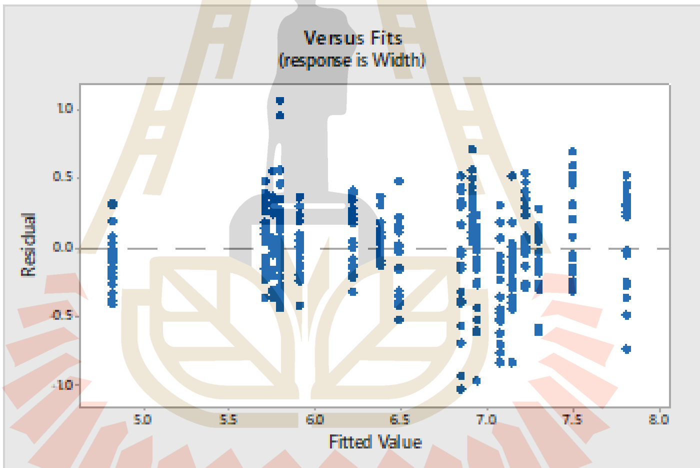


Figure 4.13 The plot of the residuals versus the fitted values

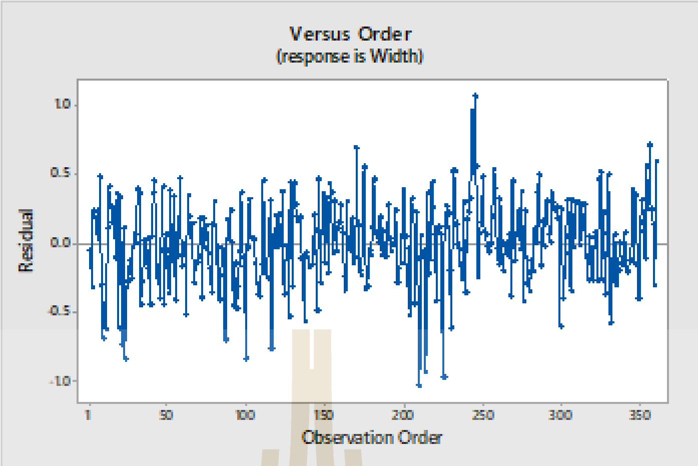


Figure 4.14 The plot of the residuals versus observation order

4.5 Analysis of the effects of main factors and interactions

The screw pitch, nozzle diameter and screw extruder velocity are the significant factors that affect the width of extruded clay filament. In addition, the significant interactions between the fasters affect the width of extruded clay filament too.

4.5.1 Analysis of the main effects

Figure 4.15 presents plots of three main effects in which the mean width at the levels of three factors were plotted. The overall mean width is equal to 6.528 mm as shown in a dash line. The linear graphs show the influence of the main factors.

I. For the screw pitch factor, the linear graphs show a negative main effect. The mean width decreases when the screw pitch decreases. There are two levels factor. The screw pitch of 18 mm denotes a low level, while 24 mm denotes a high level. The low level has a mean width equal to 6.636 mm, while the high level has a mean width equal to 6.420 mm.

II. For the nozzle diameter factor, there are three levels factor. The nozzle diameter of 5 mm denotes a low level, 6 mm denotes an intermediate level and 7 mm denotes a high level. The mean width increases from the low level to the intermediate level and decreases from the intermediate level to the high level. The low level has a mean width equal to 6.314 mm, the intermediate level has a mean width equal to 6.768 mm and the high level has a mean width equal to 6.502 mm.

III. For the screw extruder velocity factor, the linear graphs show a positive main effect. The mean width increases when the screw extruder velocity increases. There are three levels factor. The screw extruder velocity of 14 mm/s denotes a low level, 19 mm/s denotes an intermediate level and 24 mm/s denotes a high level. The low level has a mean width equal to 5.694 mm. The intermediate level has a mean width equal to 6.591 mm and the high level has a mean width equal to 7.298 mm.

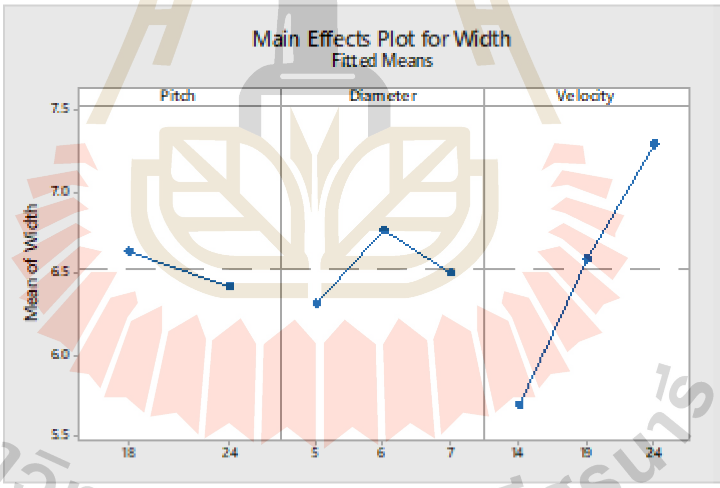


Figure 4.15 The main effect plots

4.5.2 Analysis of the interaction effects

There are the significant interactions between the screw pitch and the nozzle diameter, the screw pitch and the screw extruder velocity and the nozzle diameter and screw extruder velocity. Figure 4.16 presents plots of the interaction effects in which the linear graphs show the influence of the interaction effects.

I. The interactions between the screw pitch and the nozzle diameter indicates that the screw pitch effect is small when the nozzle diameter is at the intermediate and high level, whereas the screw pitch effect is high when the nozzle diameter is at the low level. The mean width of the intermediate and high level nozzle diameter increase when the screw pitch increases, whereas the mean width of the low level nozzle diameter decreases when the screw pitch increases.

II. The interactions between the screw pitch and the screw extruder velocity indicates that the mean width of each level screw extruder velocity decreases when the screw pitch increases. The screw pitch effect is small when the screw extruder velocity is at the low level. While the screw pitch effect is large when the screw extruder velocity is at the intermediate and high level.

III. The interactions between the nozzle diameter and the screw extruder velocity indicates that the nozzle diameter effect is small when the screw extruder velocity is at the high level. The mean widths increase when the screw extruder velocity increases from low level to intermediate level, and when the nozzle diameter increases from low level to intermediate level. The intermediate level screw extruder velocity gives the highest mean width when nozzle diameter is at the intermediate level.

The response optimization function in the Minitab program was used to estimate the optimal conditions of the parameters. The results are shown in Table 4.5, were found that if the nozzle diameter of 5 mm was used. The screw pitch should be equal to 24 mm and the screw extruder velocity should be equal to 14 mm/s. The mean width of the extruded clay filament is 5.106 ± 0.13 mm with a confidence interval of 95%. If the nozzle diameter of 6 mm was used. The screw pitch should be equal to 24 mm and the screw extruder velocity should be equal to 16.38 mm/s. The mean width of the extruded clay filament is 6.000 ± 0.069 mm with a confidence interval of 95%. If the nozzle diameter of 7 mm was used. The screw pitch should be equal to 18 mm and the screw extruder velocity should be equal to 23.12 mm/s. The mean width of the extruded clay filament is 7.000 ± 0.122 mm with a confidence interval of 95%. From these results, the means width of the extruded clay filament increases when the nozzle diameter and the screw extruder velocity increase, whereas the screw pitch decreases. The range of nozzle diameter that has been typically using in a conventional screw extruder for commercial clay printing machines is 2-10 mm (Ruscitti, Tapia and Rendtorff., 2020). The large nozzle diameter and layer high lead to poor precision dimensions and surface finish of models when compared with the small nozzle diameter and layer high. However, the smaller nozzle diameter and layer high lead to increase printing time.

Table 4.5 The optimal conditions of the parameters

Parameters			Mean width	95% CI
Nozzle diameter	Screw pitch	Screw velocity		
5	24	14	5.106	±0.13
6	24	16.38	6.000	±0.069
7	18	23.12	7.000	±0.122

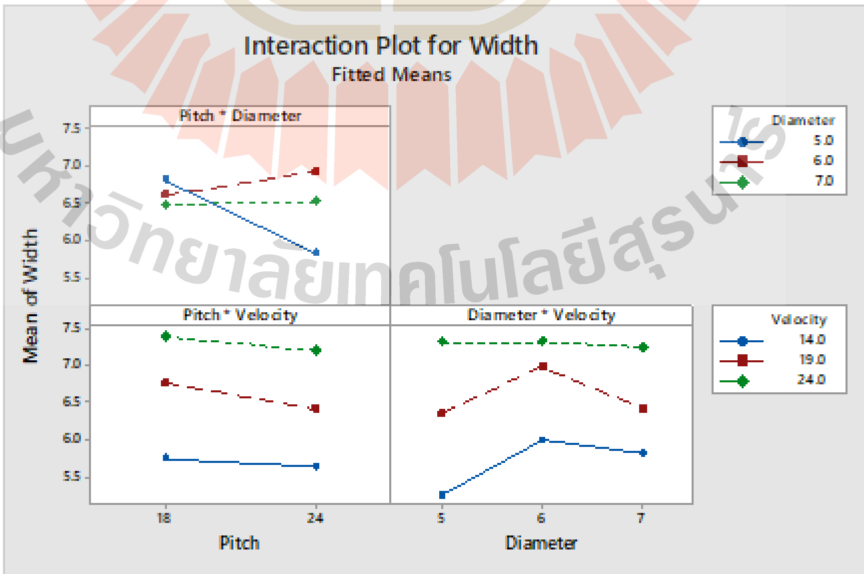


Figure 4.16 The interaction effect plots

4.6 Estimation of the width of the extruded clay filament

A fitting regression model method was used to present a relationship between the width of the extruded clay filament and the significant factors and interactions. A multiple linear regression model that are used to formulate this relationship as shown in equation 4.2.

$$\hat{Y} = \hat{\beta}_0 + \hat{\beta}_1 x_1 + \hat{\beta}_2 x_2 + \hat{\beta}_3 x_3 + \hat{\beta}_4 x_1 x_2 + \hat{\beta}_5 x_1 x_3 + \hat{\beta}_6 x_2 x_3 + \varepsilon \quad (4.2)$$

Where $\hat{Y}$ represents the width of the extruded clay filament. $\hat{\beta}_0$ represents the overall mean. $\hat{\beta}_j$, j=1, 2, ..., 6 represent the regression coefficients. x_1 represents the screw pitch (P). x_2 represents the nozzle diameter (N) and x_3 represents the screw extruder velocity (V_s). The screw pitch, the nozzle diameter, the screw extruder velocity are the significant factors. The interactions between the screw pitch and the nozzle diameter, the nozzle diameter and the screw extruder velocity are the significant interactions. Therefore, the fitted regression model for predicting the width of extruded clay filament is shown as equation 4.3. The R-squared (R^2) value of the model is 73.73% and an adjusted R^2 is 73.36%, which indicate a suitable accuracy. The predicted values that were calculated by equation 4.3 were shown in Table 4.6.

$$\hat{Y} = 11.02 - 0.5567(\mathrm{P}) - 1.130(\mathrm{N}) + 0.3494(\mathrm{V_s}) + 0.08680(\mathrm{P})(\mathrm{N}) - 0.03151(\mathrm{N})(\mathrm{V_s}) \quad (4.3)$$

Table 4.6 The predicted values of the width of extruded clay filament

Screw pitch (mm)	Nozzle diameter (mm)	Screw extruder velocity (mm/s)	Predicted value (mm)
18	5	14	5.847
		19	6.807
		24	7.766
	6	14	5.839
		19	6.640
		24	7.442
	7	14	5.830
		19	6.474
		24	7.118

Table 4.6 (Continued)

Screw pitch (mm)	Nozzle diameter (mm)	Screw extruder velocity (mm/s)	Predicted value (mm)
24	5	14	5.111
		19	6.070
		24	7.030
	6	14	5.623
		19	6.425
		24	7.227
	7	14	6.135
		19	6.779
		24	7.424

CHAPTER V

Conclusions

5.1 Conclusion

The clay printing machine was developed based on the paste extrusion process in this research. This development contributes to improving the pottery forming process. 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 the potter due to the clay models flexibly deform. In order to overcome these limitations, the clay printing machine was presented to improve pottery manually fabrication to automatic construction. In addition, the clay printing machine is able to form the clay models with complex geometry and apply to the other paste materials. That will open the new applications for various industries. The development process consists of the designing of a screw extruder, identification an appropriate formular of material and testing a capability material deposition of the machine. The principle of this machine is the deposition of clay materials through a nozzle in order to form 3D models layer-by-layer without mold and die.

The clay printing machine composes five major components as a material container for delivering system, a screw extruder for extrusion, a platform, the movement system and a control panel. The screw extruder is the key component of extrusion process in which the main functions of the extruder are compression and transportation of the clay paste through a nozzle. The clay paste is pushed along the screw channel and extruded through a nozzle by rotation of the screw. Therefore, the characters and the amount of the extruded clay filament depend on the screw character and the velocity of the rotation of the screw. To develop the capability of material deposition, the screw pitch, the nozzle diameter and the screw extruder velocity are the printing parameters, which were studied to analyze the effects of the printing parameters on the extruded clay filament. The experimental results can be summarized as follows.

5.1.1 The microstructure and clay mineral compositions of clay materials

Clay samples were analyzed microstructure by Scanning electron microscopy (SEM, Carl Zeiss AURIGA) method and evaluated clay mineral compositions by the X-ray diffraction (XRD, Burker D2 phaser) method. The Microstructure of Dan kwian clay was shown that the typical mix of rounded and flakey particles. The rounded geometry of particle shape has the lowest restriction in terms of anchoring sides limiting the flow through the printing nozzle. The XRD diffractogram of Dan kwian clay was shown that the XRD peaks of quartz and kaolinie. The quartz crystal and the structure of kaolinite do not expand when clay is added to water. Therefore, clay models that were formed by the Dan kwian clay are able to stable shape than other clay.

5.1.2 An appropriate formular of material for the clay printing machine

The different clay formulations were tested to define a proper formulation for the clay printing machine, the experimental results were found that the mean width with the clay formulation 1:0.5 (Dan kwian clay : Sand) is 6.2662 mm which is close to the expected value. In addition, each of the lines with this formulation demonstrates complete and smooth characters. Therefore, the clay formulation 1:0.5 was a suitable formulation that was used to extrude in the clay printing machine.

5.1.3 The influences of the printing parameters on the width of extruded clay filament

The experimental results of the analysis of variance were shown that the screw pitch, the nozzle diameter, the screw extruder velocity and their interactions effect on the width of the extruded clay filament. The screw pitch factor has a negative effect in which the mean width decreases when the screw pitch decreases. The screw extruder velocity factor has a positive effect in which the mean width increases when the screw extruder velocity increases. For the nozzle diameter factor, the mean width increases from the low level to the intermediate level and decreases from the intermediate level to the high level. To relate the relationship between the width of the extruded clay filament and the significant factors, a multiple linear regression model was formulated to describe this relationship as:

$$\hat{Y} = 11.02 - 0.5567(\mathrm{P}) - 1.130(\mathrm{N}) + 0.3494(\mathrm{V}) + 0.08680(\mathrm{P})(\mathrm{N}) - 0.03151(\mathrm{N})(\mathrm{V_s})$$

The R-squared (R^2) value of the model is 73.73% and an adjusted R^2 is 73.36%, which indicate a suitable accuracy. By examination of residuals, the normal plot of these residual was accepted in a normality assumption. The plots of the residuals versus the fitted value and the observation order were accepted in an independence assumption.

5.2 Recommendations for future research

5.2.1 The viscosity changing of clay material

During the experimental process, it was observed that the viscosity of clay material increases when an extrude time increases. The effect of the viscosity changing should be studied in future research.

5.2.2 Other variables

The nozzle movement speed, the distance between the nozzle and the platform and other variables should be studied to investigate the effects on the extruded clay filament.

5.2.3 Clay models

An interesting topic for future research should be studied to analyze the appearance of clay models after completely dried.

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APPENDIX I

List of Publications

List of Publications

Pitayachaval, P., Jittamai, P., and Baothong, T. (2017). A review of machining parameters that effect to wire electrode wear. **In 2017 4th International Conference on Industrial Engineering and Applications (ICIEA)**, pp. 1-4.

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An Effect of Screw Extrusion Parameters on a Pottery Model Formed by a Clay Printing Machine

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Keywords: Additive manufacturing, 3D printing, Screw extrusion, Clay

Abstract. This paper presents a study of the screw extrusion parameters that affect on the appearance of clay filament for a clay printing machine. Traditionally, pottery models are formed by using paster mold or hand throwing, which require experienced and proficient workers to form the complex pottery models. Therefore, the clay printing machine has been developed to improve manual pottery fabrication to automatic construction. This machine has been modified based on the additive manufacturing (AM). To assess a capability material deposition of the clay printing machine, nozzle diameter, screw extruder velocity, and screw pitch were investigated as the printing parameters to evaluate a quality of clay filament. Analysis of variance (ANOVA) is used to analyze main effect parameters. The experimental results showed that the 6 mm nozzle diameter, 19 mm/s screw extruder velocity and 24 mm screw pitch were the suitable 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.

Introduction

Three-dimensional (3D) printing technologies are an additive manufacturing (AM) technique which is used to fabricate 3D objects from Computer Aided Design (CAD) data. These technologies have been revolutionized in prototyping industries and have been widely applied in various 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, for example, 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 as 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 construction industries [7]. In this technique, materials were extruded through a nozzle to from 3D objects by the successive layers of material. 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 a viscous material and exhibits 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. 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 as shown in Fig. 1, a clay model is 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 paper presents a study of the screw extrusion parameters that affect on the appearance of clay filament for a clay printing machine. To assess a material deposition capability 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. 1 Pottery forming process

Literature Review

Extrusion based additive manufacturing process is a process in which material is extruded through a nozzle. Main extrusion based additive manufacturing techniques can be classified into three categories as shown in Fig. 2. 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. 2(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 [13]. To avoid these limitations, piston-based extrusion technique has been developed. A schematic of this technique is shown in Fig. 2(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 piston movement. In this technique, material degradation is the main limitation that affects on material properties [14]. In order to overcome an existing limited range of printable materials in filament-based extrusion and material degradation in piston-based extrusion, screw-based extrusion technique has been developed. A schematic of this technique is shown in Fig. 2(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 [15]. Initially, Screw based extrusion technique was introduced to fabricate physical models for rapid production of ceramic and polemic parts. Screw extruder printer was developed to print high-viscosity material and conditions of screw extrusion were optimized [16]. 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. The extrusion performance of viscous ceramic paste was investigated by comparing three different extrusion methods (ram extruder, shutter valve, and auger extruder-based method). The results showed that the auger extruder-based method showed more accuracy of the start and stop of extrusion and more consistency extruded filament width than other methods [17]. 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 [18]. Rheology is an important property of materials, which is provided for good extrudability and stability. The rheological properties of mashed potatoes with addition of potato starch was designed to investigate printing behavior by using extrusion-based printer. 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 [19]. In ceramic industry, extrusion-based technologies have been applied to fabricate ceramic products that are formed based on ceramic clay. Zhang and Yang [20] 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 compared with traditional fabrication methods. To improve 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.

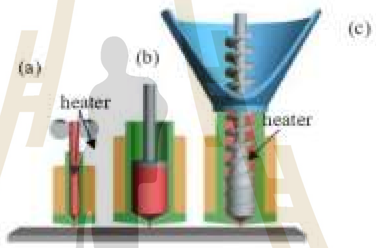

Fig. 2 Extrusion based techniques [21]: (a) filament-based extrusion, (b) piston-based extrusion, (c) screw-based extrusion

Method and Material

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. 3: (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 motor 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.

Material. The consideration material is Dan Kwian clay in which a traditional material in north east 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].

Fig. 3 The clay printing machine: (a) material container, (b) screw extruder, (c) movement system

Table 1 Experimental 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

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 experimental 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. 4(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. 4(b). The expected width of clay filaments is equal 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 depends 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. 5: 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. 5(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. 5(b).

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.

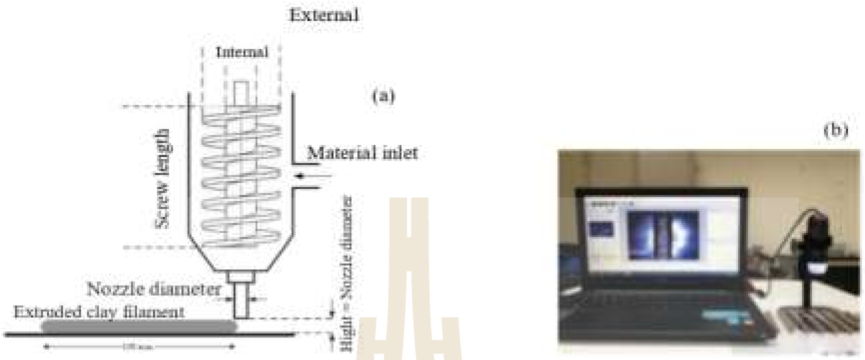

Fig. 4 Experimental process: (a) schematic diagram of extrusion clay process, (b) digital microscope

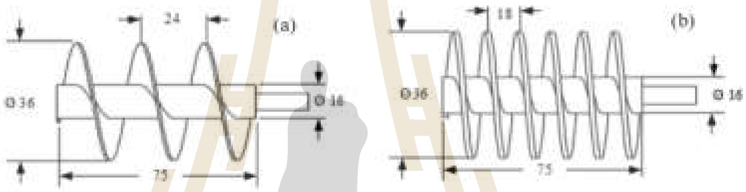

Fig. 5 Two screw types (Unit: mm): (a) short pitch, (b) half pitch

Result 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. 6 and 7 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 that low screw extruder velocity (14 mm/s) showed 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. 6 (g) and 7 (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 Figure 6, while a 24 mm screw pitch showed the straight lines which present smoothest surface as shown in Fig. 7. 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 which is 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. 8(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 in 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. 8(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. 8(b). This interaction illustrated that the screw extruder velocity has small effect on each level of the nozzle diameter. The middle level of screw extruder velocity showed the best performance. A normal probability plot of the residuals was shown in Fig. 8(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. Therefore, 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 is used to formulate this relationship.

$$\gamma = \beta_0 + \sum_{j=0}^{k} \beta_j \chi_j + \varepsilon \qquad (1)$$

Where γ is a response variable with k regressor 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.

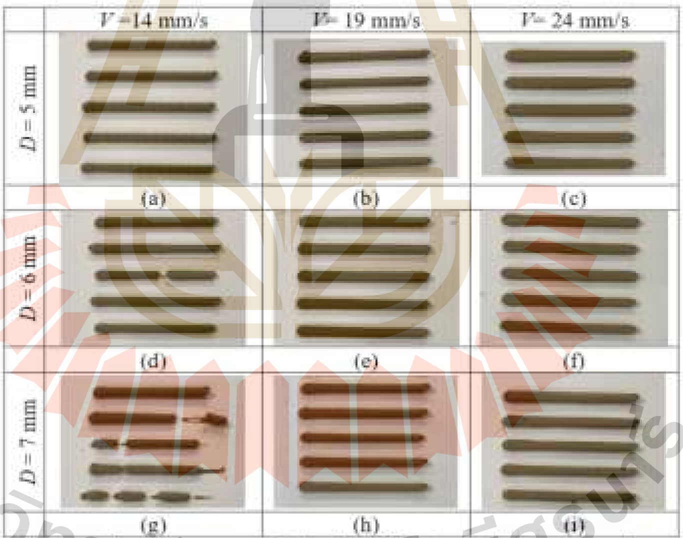

Fig. 6 Clay filaments for 18 mm screw pitch with different nozzle diameter and screw extruder velocity

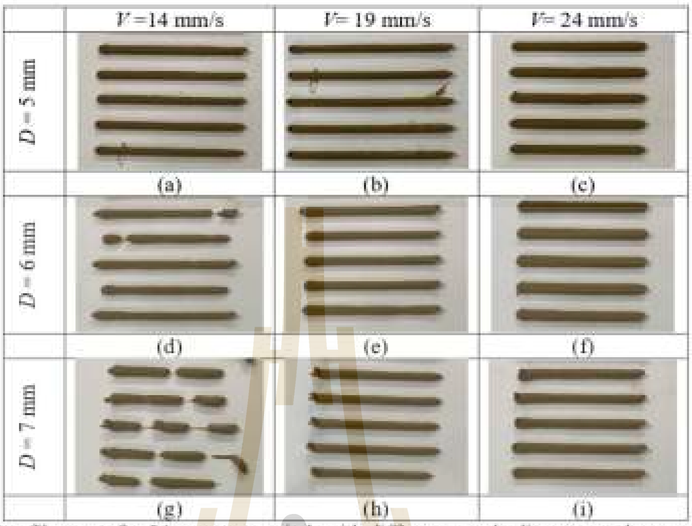

Fig. 7 Clay filaments for 24 mm screw pitch with different nozzle diameter and screw extruder velocity

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			

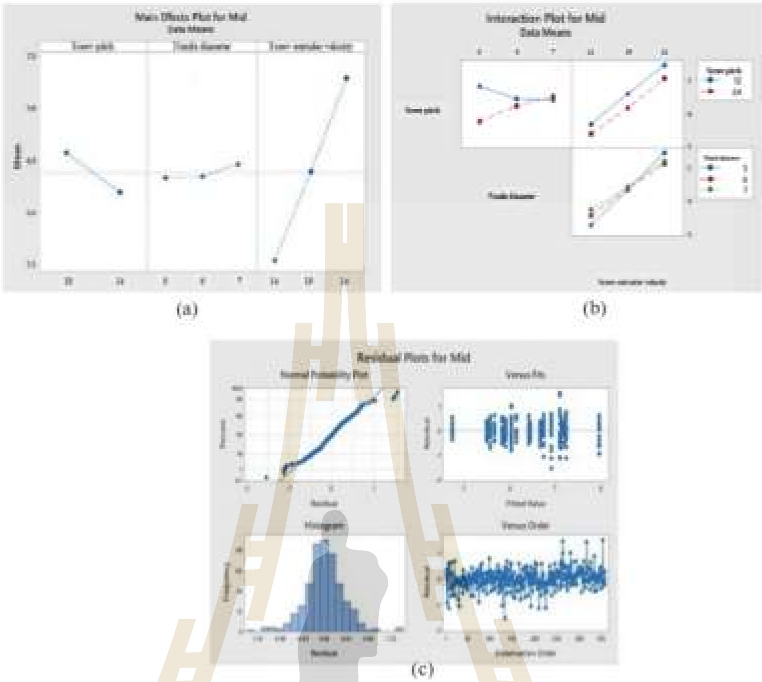

Fig. 8 DoE analyze: (a) Main effect plots, (b) Interaction plots, (c) Residual plots

Conclusion

This paper has presented a newly clay printing machine. The machine has been developed based on the additive manufacturing technique in which improves manual pottery fabrication to automatic construction. 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. To evaluate the performance of the machine, three parameters including the nozzle diameter, the screw extruder velocity and the screw pitch, were verified the capability of material extrusion of the clay printing machine. The results of the experiment confirmed that the nozzle diameter, the screw extruder velocity and the screw pitch are critical parameters on the geometry of extruded clay filaments. The 6 mm nozzle diameter, 19 mm/s screw extruder velocity and 24 mm screw pitch were optimal printing parameters for providing an appropriate geometry of extruded clay filament. 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 indicates a suitable accuracy. Therefore, the clay printing machine presented in this study can be used to produce pottery models. The future research is to identify suitable conditions for performing a complex 3D printing pottery.

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A Review of Process Parameters That Effect to Extrusion on Demand

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Abstract. An additive Manufacturing (AM) process has been introduced to fabricate three-dimension objects from liquid polymers and powder particles e.g. polymers and metals, this process has been also applied to fabricate three-dimension ceramic objects called paste materials which compose of liquid and solid components. To build additive model, the paste material is extruded via pressure force through the nozzle by using ram extrusion, then the model is constructed layer-by-layer on the table to form designed shape. To improve a capability of extrusion process, the Extrusion On Demand (EOD), that refers to the ability of paste extrusion to regulate start and stop, has been developed to improve an accuracy of material deposition. This paper presents a review of process parameters that effect to extrusion on demand such as ram velocity, Dwell time, paste property and extrusion mechanisms.

1 Introduction

Additive manufacturing (AM) is a technology that fabricate three-dimensional (3D) objects by adding material layer-by-layer directly from CAD (Computer Aided Design) model [1]. Traditional AM technologies have been used to fabricate 3D objects based on a raw material states that are liquid-based, solid-based, and powder-based, for example liquid polymers and powder particles including polymers and metals. These materials contains some disadvantages such as high melting point and high cost of raw materials [2]. To solve those disadvantages, paste materials have been applied to fabricate three-dimension parts in additive manufacturing. Pastes material is a kind of material composed of solid and liquid state [3]. Pastes are states that are made up from many different substances and formed by using extrusion method. The paste extrusions have been applied for various industries such as ceramic parts, cosmetic pencils, tiles, food manufacturing, animal feeds, and PTFE wires [4]. Extrusion is carried out by pressing pressure to ram extruder, as illustrated in Figure 1 (a). Normally, the ram extrusion consists of control system and extrusion device. In paste extrusion process, the pressure is generated to force the paste through a nozzle. The paste flow is regulated by controlling the ram movement, which moves down to extrude paste material. The extrudate is deposited layer-by-layer on the table to form designed shape. To improve a capability of extrusion process, Extrusion On Demand (EOD), that refer to the ability to regulate the start and stop of paste extrusion, has be developed to improve material deposition. This paper presents a review of process parameters that effect to extrusion on demand such as ram velocity, Dwell time, paste property and extrusion mechanisms.

2 The paste extrusion process

The Process of paste extrusion is generally carried out in three steps: paste preparation, Forming, and Finishing [3]. In paste preparation, powder components and liquid are mixed in suitable mass proportion to carry out a paste. These components are contained in the barrel. In forming, Pressure is generated to force the paste through a nozzle. Then, the paste is extruded from an extruder by using ram extrusion. The extrudate is deposited layer-by-layer to form a model. During finishing stage, the extrudate is solidified by thermal processing during this stage. Since a conventional extrusion method extrudes the paste by using ram extruder, the extrudate contained head and tail effect as shown in Figure 1 (b). The quality of designed shape depends on these effects. To achieve the accuracy and quality of designed shape, the conventional extrusion method has been improved to control the start and stop extrusion on demand in order to enhance the performance of the extrusion process. In additional, the ram velocity, Dwell time, paste property and extrusion mechanisms are main parameters that influence on the paste extrusion process.

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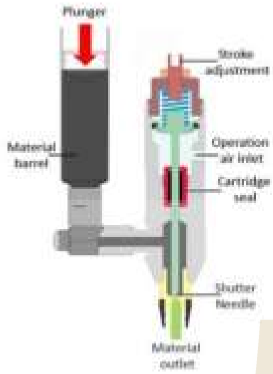
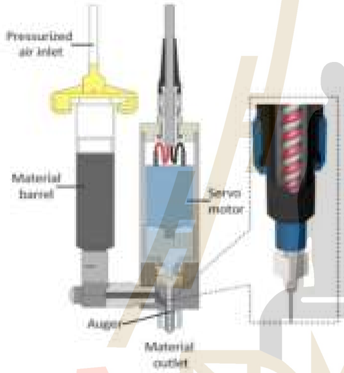


(b) Needle valve



(c) Auger valve

Figure 2. Schematic diagram of ram extruder, needle valve and auger valve extrusion [5]

To improve a capability of extrusion performance, the ram velocity, Dwell time, paste property and extrusion mechanisms are main parameters that have been studies to investigate the effect on the ability extrusion on demand for paste extrusion processes as shown in table 1. Mason et al. (2007) modified the traditional ram extrusion mechanism in order to improve the extrusion on demand. Load cell housing was added to connect directly with the plunger, while plastic syringe was replaced by metal barrel. A new ram extrusion mechanism was implemented to print the line tests with a set of ram retreating velocities (0, 0.25, 0.5, 1, 1.5, 2, 2.5, and 3 mm/s) and extrusion forces of 308N. The results were found that the ram retreating velocities that are higher 2 mm/s able to stop on the extrusion on demand. The influence of the ram velocity on the extrusion force and liquid phase migration in Freeze from Extrusion Fabrication process was studied. Liu and Leu (2009) experimented to investigate liquid phase migration for aqueous Al_2O_3 paste. The aqueous paste and five ram velocities (10, 5, 2, 1.5, 1 μm/s) were used for investigation in this study. The experimental results were shown that highly liquid phase migration was found when ram velocity was lower than 5 μm/s. Oake et al. (2009) present an experiment to investigate the Dwell times that effect to extrusion filament. In this experiment, the Dwell time is set as a function of the reference ram force. This force is applied to activate for paste extrusion. Values experiment are 50%, 55%, 60%, 65% and 70% of the reference ram force 450 N and 475 N. The results were shown that the discontinued filaments were presented at Dwell time less than 65%. In addition, the increasing of the reference ram force from 450 to 475 N was found the accumulation material at the start of filaments. This indicates that a row ram force should be used for extrusion process. Liu et al. (2013) conducted an experiment to study the influence of ram velocity and paste properties on extrusion process by applying series of ram velocities (2,5,10 and 15 μm/s) and three pastes with difference viscosity. The results were found that the extrusion pressure shown an increasing slowly with high velocities (10 and 15 μm/s) whereas the extrusion pressure shown an increasing rapidly at low velocity (2 and 5 μm/s). Therefore, at low velocity, liquid phase was moved into an extrudate. So the remaining paste in the barrel become drier. Drier paste in the barrel need high pressure force to press the paste flow. In addition, the ram velocity of 2 μm/s was experimented to study effect of paste viscosity on liquid phase migration. The results were found that liquid phase migration was found when a higher viscosity paste is used with the lower ram velocity. The paste viscosity had significance effect on extrusion process [12]. The high viscosity of paste materials means a high amount of solid particles. Therefore, high extrusion force had be needed to extrude materials whereas low viscosity paste lead to difficult to form the designed shape. Li et al. (2017) have conducted an experiment to study the influence of extrusion mechanisms, Dwell time and paste property on the start and stop of extrusion. The start Dwell time for ram extrusion, needle valve and auger valve mechanism was 450, 70 and 0 ms respectively. Those mechanisms were used to experiment the ability of extrusion on demand. Dash line printing tests were conducted for all three methods. The line printing tests were printed from right to left and compared the tail and head effect of the printed lines to indicate the capable extrusion start and stop by using the image dash line segments printed. The experimental results were shown that the dash line segments printed by the needle valve and auger valve methods have shorter tails than the ram extrusion method because the start and stop dwell time of the needle valve and auger valve methods are shorter than the ram extrusion method. Then, the filaments with short start Dwell time shown the accuracy of the start and stop of extrusion.

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Table 1. Overview of the main extrusion process parameters that effect to extrusion on demand

References	Ram velocity	Dwell time	Past property	Extrusion mechanism
[8]	✓	-	-	-
[9]	✓	-	✓	-
[10]	✓	✓	-	-
[11]	✓	-	✓	-
[5]	-	✓	✓	✓

3 Conclusion

The extrusion methods have been widely used to fabricate 3D objects from paste materials. Those materials are made up from liquid and solid particle. The ram extrusion method is widely used to form paste materials. In this method, pressure force was generated to press paste material through a nozzle by using ram extruder. To improve a capability of extrusion process. The four main parameters were reviewed. The ram velocity, Dwell time, paste property and extrusion mechanisms are those parameters that influence on the paste extrusion process. The ram extruder, needle valve and auger valve based extrusion method were experimented to print the line tests. Because of the shorter Dwell time, needle valve and auger valve shown the ability start and stop of extrusion on demand better than the ram extrusion.

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A Review of Machining Parameters that Effect to Wire Electrode Wear

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***Abstract*—Wire electrical discharge machining (WEDM) or Wire-cut EDM is a non-traditional machining process, This process is a spark erosion process. That erodes material from work piece by a successive of electrical discharges. The spark erosion process is occurred between work piece and wire electrode. The wire electrode is used as the cutting tool. WEDM is widely used to cut high complexity shapes and present high accuracy. The advantage of WEDM is the capable cutting of hard metals that are difficult to cut with other process. To establish a quality of this process, material removal rate (MRR), surface finishing (SF), Kerf width and wire wear ratio (WWR) are measured. However, a life of cutting tool has been concerned, as wire wear ratio. This paper presents a review of machining parameters that effect to wire wear ratio. Pulse on time, pulse off time, peak current, servo voltage, gap voltage, dielectric flow rate, wire feed rate and wire tension are machining parameters which influence to wire wear ratio.**

Keywords-wire electrical discharge machining; wire electrode; wire wear ratio

I. Introduction

Wire electrical discharge machining (WEDM) is a non-traditional manufacturing process that is widely used to cut a complexity shapes and a hardness material. WEDM or Wire-cut EDM is a spark erosion process that material is eroded by wire electrode as the cutting tool. The spark erosion process occurs between wire and work piece, in which those are not contract together. This process is occurred by electrical discharging between the gap of wire and work piece. The gap between wire and work piece is retained by the control system in order to produce the smooth cutting surface [1]. Normally, WEDM machine consists of power devices, machine tools and flushing device. The capabilities of WEDM process depend on material removal rate (MRR), surface finish (SF), Kerf width and wire wear ratio (WWR). Those performance are performed base on machining parameters such as pulse on time, pulse off time, peak current, servo voltage, gap voltage, dielectric flow rate, wire feed rate and wire tension. Mahapatra and Patnaik [2] experimented to study the effect of machining parameters on material removal rate and surface finish. Taguchi method was used to identify optimal machining parameters for maximum material removal rate and surface finish in this study. Tosun [3] studied the cutting performances (cutting speed and surface roughness) in WEDM. Pulse time, Open circuit voltage, wire speed and dielectric fluid pressure are cutting parameters. Those parameters were investigated the effect of the cutting performances.

Wire wear ratio is a significant variable because the wear ratio performs tool failure due to the erosion also occurs on the wire electrode. In addition, a wire breakage or a wire rupture is one problem of tool failure in WEDM, which is terminated the cutting process. This breakage also affects the production cost. Gamage and DeSilva [4] studied the energy consumption with unexpected wire breakage during machine operate. The several wire breaking lead to a long processing time and give a poor quality surface of output, while increases the energy consumption.

This paper presents a review of machining parameters that effect to wire electrode ware. The WEDM process presents in the next section. The process parameters and the effect of parameters on wire electrode wear are reviewed.

II. WEDM Process

WEDM is a spark erosion process. The material extraction is occurred by the series of electrical sparks between work piece and wire electrode [5]. The wire electrode is used as the cutting tool but the wire is not contract the work piece. WEDM consists of a wire electrode, a wire guiding, dielectric supply, machine table and other control devices. A schematic diagram of WEDM shown in Fig. 1. The wire electrode feeds through the wire guiding and passes through work piece. The work piece is fixed on the machine table and the moveable table is controlled by control device. During process, the work piece is immersed in a dielectric fluid that cools cutting process and removes out the eroded debris. The voltage is applied between work piece and wire electrode. The ionization of dielectric fluid is stated. This process changes the properties of dielectric fluid from an insulator to an ionic particle, which allows electrical current to pass from wire electrode to work piece, called sparking. Spark is generated between a gap wire electrode and work piece. The spark erosion occurs on work piece surface. The movement wire electrode is controlled by a computer numerical control (CNC) system to cut the designed shape. To achieve successful the cutting process, there are several parameters that relate the performance of WEDM machine. The most important performance measures are metal remover rate, surface finish and wire ware ratio. Those performance measurements are depended on the setting machine parameters such as pulse on time, pulse off time, peak current, servo voltage, gap voltage, dielectric flow rate, wire feed rate and wire tension.

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A. Wire Wear Ratio

The wire wear ratio (WWR) is studied to minimize the tool failure. WWR is calculated following equation (1):

$$WWR = WWL / IWW \quad (1)$$

WWL is the loss of the wire weight and IWW is the initial wire weight. Several researches investigated the effect of different machining parameters on WWR. Tosun and Cogun [8] experimented to investigate the effect of machining parameters on the wire wear ratio. Pulse duration, open circuit voltage, wire speed and dielectric fluid pressure are machining parameters. The statistical techniques were used to indicate the significant of those parameters on the WWR. The experiments were performed on a Sodick A320/EX21 WEDM machine by using brass wire of 0.25 mm diameter as tool and AISI 4140 steel of 10 mm thickness as work piece material. The result was found that the increasing of pulse duration and open circuit voltage increase WWR, but the increasing of wire speed and fluid pressure decrease WWR. Based on ANOVA result, the open circuit voltage and the pulse duration were the most effective on those parameters. Mevada, Shah and Khatri [9] experimented to fine out the WWR at the different machining parameter such as peak current, pulse on time and pulse off time. The analysis of variance was used to determine the effect of those parameters. The experiments were performed on CNC wire cut Electro discharge machine. Molybdenum wire of 0.8 mm and EN-8 material were used as a tool and work piece for the experiment. The result was found that the increasing in peak current presented gradually WWR but, the increasing in pulse on time established more WWR. While pulse off time is not much affects on the WWR. Ramakrishnan and Karunamoorthy [10] considered multi responses of WEDM process. Each experiment has been studied the multiple performances such as material removal rate, surface roughness and wire ware ratio for WEDM process under cutting conditions such as pulse on time, wire tension, delay time, wire feed speed and ignition current intensity. ANOVA was used to identify the pulse on time and ignition current intensity that two parameters influence more than other. Bobbili, Madhu and Gogia [11] experimented to study the effect of cutting parameters on the size of crater and wire wear ratio. The experiments were conducted under the different cutting parameters such as open circuit voltage, pulse duration, wire speed and flushing pressure. The data of wire crater dimensions were collected and analyzed relationship between the cutting parameters and the performance. The result was found that the most effective machining parameters were open circuit voltage and pulse duration but, dielectric fluid pressure and wire speed were less effect machining parameters. Rangnath, Sudhakar and Srikantappa [12] experimented to study wire erosion wear. The experiments were performed on Electra elcut-334. Mild steel, OHN steel and HCHCr steel were used as work piece. Bare brass and zinc coated brass wires were used as tool to study of this experiment. The result was found that discharge current and discharge time affect on wire erosion wear, which leads to wire failure.

B. Wire Breakage or Wire Rupture

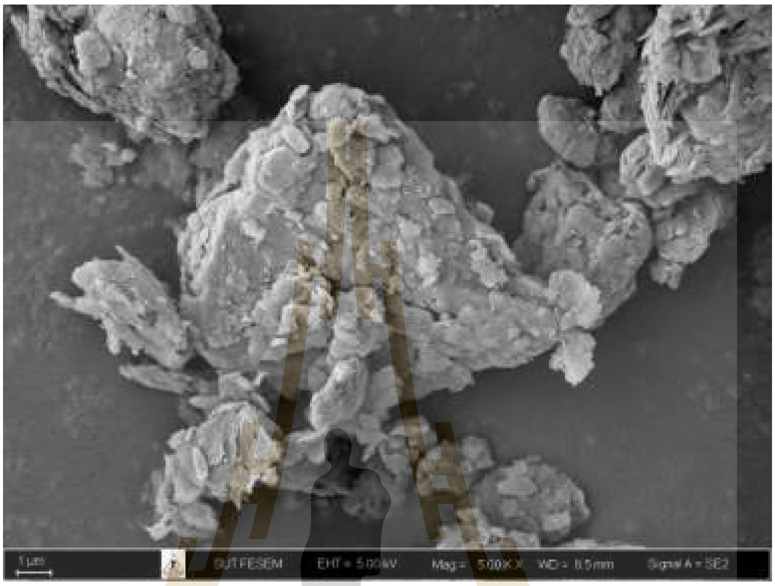
Various parameters are used to study wire failure of WEDM in order to prevent wire breakage. More researches have been studying the effect of parameter on the wire breaking. Kinoshita, Fukui and Gamo [13] observed the effect of pulse frequency. The result was shown that the pulse frequency of gap voltage rapid rise for approximately 5–40 ms before wire breakage. Then, they developed a monitoring and control system that detected the sudden rise of plus frequency. The pulse generator and servo system was turned off to prevent from the wire breaking when the sudden rise of plus frequency was detected, but it affected the machine efficiency. Luo [14] investigated the spark characteristics, the temperature distribution, the rapture mechanism and the mechanical strength of the wire to determine the effect mechanical strength of wire. Material yielding and fracture were the cause for wire breakage, while a temperature increase aggravates the failure processes because the wire strength was reduced at high temperature. Cabanes, Protillo, Marcos and Sanchez [15] studied the cause of wire breakage in order to detect the risk of wire breaking. Peak current, discharge energy and ignition delay time were evaluated to analyze the effect on wire breakage. Anish, Vindo and Jatinder [16] studied the effect of six input parameters such as pulse on time, pulse off time, peak current, spark gap voltage, wire feed and wire tension. The experiments were indicated the wire breakage frequency continuously increases with an increase in pulse on time, peak current and wire tension whereas decrease pulse off time and spark gap voltage. Okada, Konishi and Kurihara [17] experimented to investigate the influence of machined kerf length on wire breakage. The result was found that the wire breaking often occurred at a particular short machined kerf length. The increasing crater size on the wire was a cause the risk of wire rupture. Tosun, Cogun and Pihtili [19] studied to investigate the effect machining parameters on wire crater size (the crater diameter and dept). Pulse duration, open circuit, wire speed and dielectric flushing pressure are machining parameters. The result was shown that the increasing of pulse duration, open circuit voltage and wire speed increased the crater diameter and crater dept.

Those experiments indicated the various researches on the wire electrode ware in WEDM process. The machining parameters were studied to investigate the effect of machining parameters on wire wear ratio, the wire breakage and wire rupture as shown in Table I. The wire wear ratio is a significant variable, which leads to wire failure. The wire wear ratio is the weight loss wire electrode after cutting divided by the initial wire weight. The wire wear ratio studies to minimize the tool failure. Those experiments found the increasing of pulse duration and open circuit voltage increase the wire wear ratio. Those parameters are most impact on wire wear ratio. The rapidly changing pulse duration and peak current lead to wire breakage or wire rupture, in which a quality of surface finish and machining accuracy are decreased.

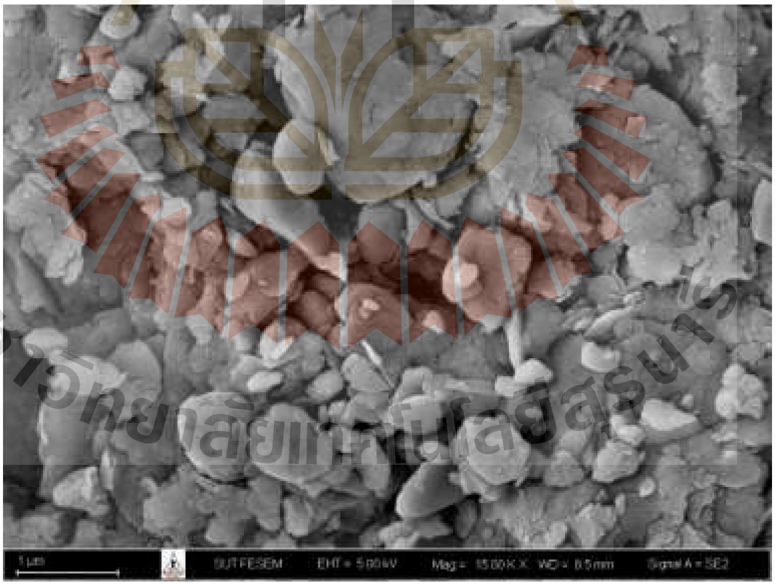
APPENDIX II

Microstructures of Clay Materials

Microstructures of Clay Materials

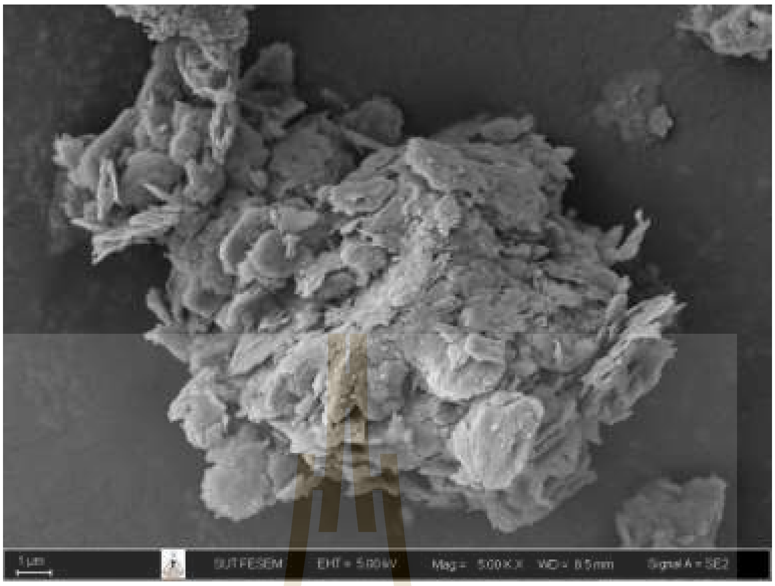


(a)

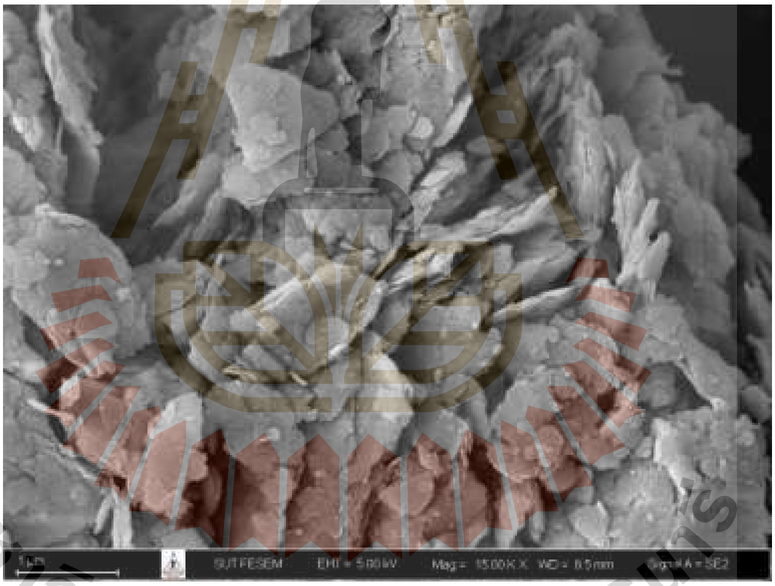


(b)

Figure A 2.1 The SME images of the Dan kwian clay : (a) x5,000 magnification and (b) x15,000 magnification

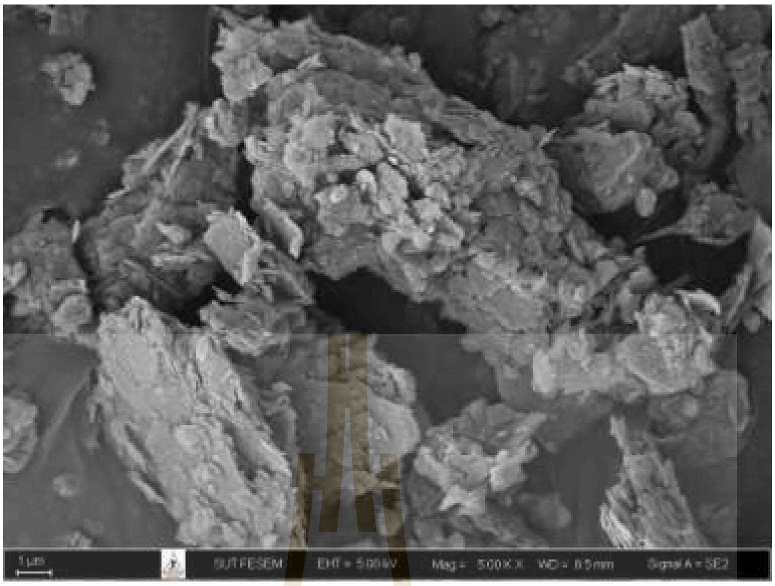


(a)

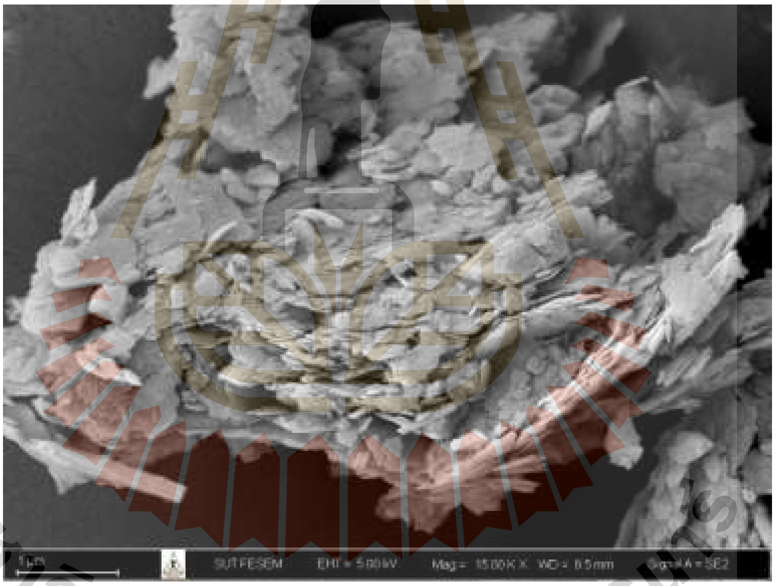


(b)

Figure A 2.2 The SME images of the Ratchaburi red clay : (a) x5,000 magnification and (b) x15,000 magnification



(a)



(b)

Figure A 2.3 The SME images of the Compound lampang clay : (a) x5,000 magnification and (b) x15,000 magnification

BIOGRAPHY

Mr. Thanakharn Baothong was born on July 1, 1988 in Surin Province, Thailand. He received his Bachelor's Degree in Industrial Engineering from Suranaree University of Technology (SUT) in 2011. He then continued his Master's Degree in Industrial Engineering at Suranaree University of Technology and graduated with his Master's Degree in 2013. After graduation, he worked as a process engineer at KOHLER company for 1 year. After that, he applied to study Doctor's Degree in Industrial Engineering at Suranaree University of Technology in 2015.