PRODUCTION OF FILAMENT FROM HIGH DENSITY POLYETHYLENE (HDPE) WASTE USING CUSTOM MADE MINI EXTRUSION MACHINE

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DECLARATION

I hereby declare that this thesis submitted to Universiti Malaysia Sabah (UMS) as partial fulfilment of the requirements of bachelor's degree in Mechanical Engineering and has not been submitted to any other university for any degree. I also certify that the work described herein is entirely my own, except for quotation and summaries sources of which have been duly acknowledged.

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1 JULY 2022

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CERTIFIED BY

Ir. Ts. Dr. Melvin Gan Jet Hong
SUPERVISOR

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ABSTRACT

This project aimed to produce a filament from high density polyethylene (HDPE) waste using a tabletop extrusion machine that priorly custom-made in the Mechanical Engineering Lab. The project was carried out in three stages which were modification stages, filament extrusion stages and testing filament stage. Based on the modification, motor with a higher torque is the best motor for extrusion machine. For the filament extrusion, the suitable temperature and speed for the extrusion machine to produce a HDPE filament is 225°C and 35rpm. 777cm of HDPE filament was produced using 50g of HDPE flakes. For the filament testing, the roundness of the HDPE filament has a significant defect in the beginning of the filament however it gets lesser throughout the end of the filament. Diameter of the HDPE filament produced is in between the range of 1.6mm to 3.7mm, it means that the diameter of the filament is not consistent enough. The HDPE filament produced do not have any porosity in the cross section and surface of the filament. The hardness of the HDPE filament produced is in between the range of 39HD to 53HD, and the hardness is decreasing compared to the hardness of HDPE flakes. Surface roughness testing found that the surface of HDPE filament is not smooth enough in the beginning of the filament, but it gets smoother throughout the end of the filament. Based on the results, it shows that the objectives of the study are achieved as well as all the questions of the study are answered throughout this project. However, there are still room for improvement in order to produce a good quality of filament.

ABSTRAK

Projek ini bertujuan untuk menghasilkan filamen daripada sisa polietilena berketumpatan tinggi menggunakan mesin penyemperitan atas meja yang sebelum ini dibuat khas di Makmal Kejuruteraan Mekanikal. Projek ini telah dijalankan dalam tiga peringkat iaitu peringkat pengubahsuaian, peringkat penyemperitan filamen dan peringkat ujian filamen. Berdasarkan pengubahsuaian, motor dengan tork yang lebih tinggi adalah motor terbaik untuk mesin penyemperitan. Untuk penyemperitan filamen, suhu dan kelajuan yang sesuai untuk mesin penyemperitan menghasilkan filamen HDPE ialah 225°C dan 35 putaran seminit. 777cm filamen HDPE dihasilkan menggunakan 50g kepingan HDPE. Untuk ujian filamen, kebulatan filamen HDPE mempunyai kecacatan yang ketara pada permulaan filamen namun ia semakin berkurangan sepanjang penghujung filamen. Diameter filamen HDPE yang dihasilkan berada di antara julat 1.6mm hingga 3.7mm, bermakna diameter filamen tidak cukup konsisten. Filamen HDPE yang dihasilkan tidak mempunyai sebarang keliangan pada keratan rentas dan permukaan filamen. Kekerasan filamen HDPE yang dihasilkan berada di antara julat 39HD hingga 53HD, dan kekerasan semakin berkurangan berbanding kekerasan kepingan HDPE. Ujian kekasaran permukaan mendapati permukaan filamen HDPE tidak cukup licin pada permulaan filamen, tetapi ia menjadi lebih licin sepanjang hujung filamen. Berdasarkan keputusan tersebut menunjukkan objektif kajian tercapai serta segala persoalan kajian terjawab sepanjang projek ini dijalankan. Walau bagaimanapun, masih terdapat ruang untuk penambahbaikan bagi menghasilkan kualiti filamen yang baik.

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LIST OF ABBREVIATION

3D	Three-Dimensional
ABS	Acrylonitrile Butadiene Styrene
AM	Additive Manufacturing
ASTM	American Society for Testing and Materials
CAD	Computer Aided Design
FDM	Fused Deposition Modelling
FPF	Fused Particle Fabrication
FSSA	Faculty of Sciences and Natural Resources
FOE	Faculty of Engineering
HDPE	High Density Polyethylene
HIPS	High Impact Polystyrene
LDPE	Low Density Polyethylene
LLDPE	Linear Low-Density Polyethylene
MFI	Melt Flow Index
MFR	Melt Flow Rate
PET	Polyethylene Terephthalate
PID	Proportional-Integral-Derivative
PLA	Polylactide or Poly-lactic Acid
TGA	Thermal Gravimetric Analysis

LIST OF SYMBOLS

HD	Hardness
Hp	Horsepower
T_g	Glass transition temperature (°C)

CHAPTER 1

INTRODUCTION

1.1 Overview

3D printing technology is widely used in many fields. 3D printing technology is a truly innovative and has emerged as a versatile technology stage (Shahrubudin, 2019). Being able to construct complex three-dimensional (3D) objects by depositing materials layer by layer, additive manufacturing (AM), in particular, 3D printing has become a fast-developing manufacturing technique nowadays (Liu , 2017). 3D printing can directly print the desired object by making a virtual design of the object you want to create. This virtual design is created in a Computer Aided Design (CAD) file with a 3D modelling application or a 3D scanner. One of the methods of 3D printing is by melting and laying filament down to slowly build up the model in layers in a process known as "Fused filament fabrication (FFF)" or "Fused deposition modelling (FDM)" (Daniela *et al.*, 2018).

There are many different materials of 3D printing filament that can be used with Fused deposition modelling (FDM). The most popular are Acrylonitrile Butadiene Styrene (ABS), Polylactic Acid (PLA), and Nylon (Polyamide), although other exotic materials, such as a material blend of plastic and wood or carbon, can also be used. However, Acrylonitrile Butadiene Styrene (ABS) and Polylactic Acid (PLA) are categorized as Type 7 or "other" by International Resin Identifier Codes, they cannot be recycled as regular thermoplastic materials because they would remain solid during the recycling process, causing issues for the recycling facility. Other thermoplastic materials have been explored by researchers for use as 3D printing filament and this effort will definitely overcome the recycling issues of Acrylonitrile Butadiene Styrene (ABS) and Polylactic Acid (PLA) as a 3D printing filament (Griffin, 2021).

An extruder is a machine that is commonly used in industry. This machine is not only used in the operations of filament extrusion but also used in plastic moulding operations. Usually in the plastic industry, they used screw extruder. There are two types of extrusion machines that widely used in the field: the single and the twin screw extruders. These machines have the following main components: electric motors, drivetrain, bearing, feeding system, screw, heating and cooling system, barrel, die and temperature and pressure sensors (Gyarfas & Gergely, 2019). The example of extrusion machine is shown in figure 1.1.

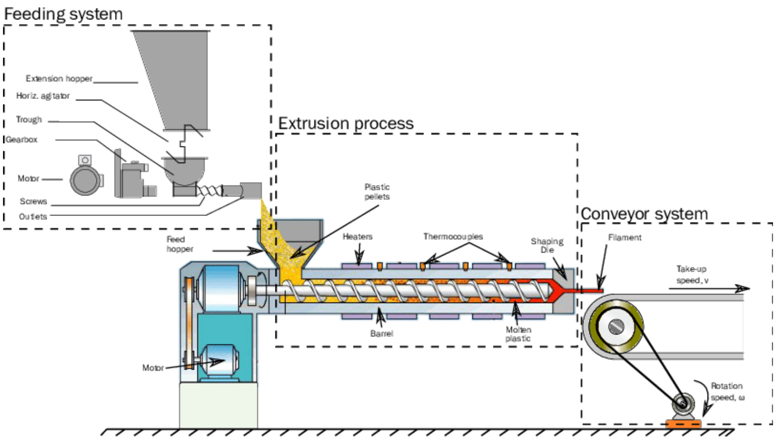

Figure 1.1: Extrusion Machine
Source : (Fabio *et al.*, 2017)

The design of the screw of an extruder is vital as the products' stability and the quality is vastly dependent with it. The extruder barrel that located outside the screw provides the capabilities of heating and cooling. Feed hopper and barrel are connected by a feed throat which designed to hold the plastic pellet. It will also allow them to flow into the barrel steadily. There is a die in the end of the extruder which help to decide the product's shape. The heaters are added to an extruder. This is to ensure that the extrusion process can be completed. Hence, it will help to produce useful products (Marko *et al.*, 2020).

In the extrusion machine, the screw inside the extruder's barrel rotates, powered by motor. This rotation of the screw is going forward to the end of the barrel with nozzle attached. When plastic bit feed into the screw, the plastic bit fills the inner diameter of the screw and force to moves forward according to the screw movement. This action develops shear stress caused by the friction of plastic bits and the screw inside the extrusion barrel, thus melts the plastic. The plastic melt is push forward and with enough pressure the melted plastic material pushes through the nozzle. The plastic comes out from the extrusion machine may be used to produce filament of plastic or push into a plastic die to form plastic product.

An extrusion machine has become one of the important machines in processing waste plastic materials into product. One of the examples is producing filament from waste 3D printer's product or even other waste thermoplastic material.

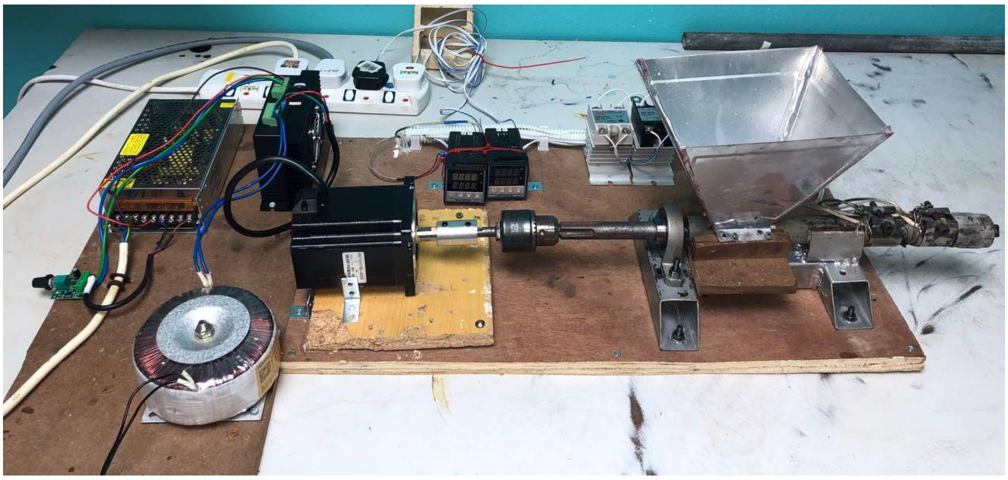

Figure 1.2 : Extrusion Machine in Lab FKJ
Source : Extrusion machine at Mechanical Engineering Lab, in the FKJ.

Many research have been conducted to determine the appropriateness of using thermoplastic materials other than PLA and ABS, including pure thermoplastics and recycled thermoplastics. High impact polystyrene (HIPS) was found as a form of pure thermoplastic with a low-cost polymer and classified as a low strength structural use where low-cost impact strength, machinability, and manufacturing are required (Kumar *et al.*, 2018). It is commonly used for the preparation of prototypes due to its high dimensional stability and simplicity of manufacture, joining, and painting. Although it is recyclable, because of its poor resistance to organic solvents, it takes a long time to degrade. Polyethylene terephthalate (PET) and polypropylene (PP) are the two most common waste plastics used in the Fused Particle Fabrication (FPF) process, where recycled polymers have the potential to expand fast in the 3D printing field for recycled materials (Aubrey *et al.*, 2018). PET is the most recycled plastic, with Type 1 as the material standard, and it is well known for its use in plastic bottles. According to research, recycled PET (rPET) outperforms fresh PET (Mark *et al.*, 2019). However, because of its sensitivity to flow in low viscosity, the spooling process becomes more difficult, resulting in a non-uniform diameter of the filament produced. Meanwhile, recycled polypropene (rPP), which is also one of the most frequent types of plastic found in household garbage, is unsuitable for use as 3D printing filament due to significant warping and poor layer adhesion during printing. Nowadays, more focus has been put on High Density Polyethylene (HDPE) material since it is the simplest thermoplastic polymer to recycle and is accepted at recycling facilities all over the world, and it has a recycling sign of a number 2. Thus, this paper will discuss on the extrusion machine and how works in production of the filament from HDPE waste.

1.2 Problem Statement

Researchers have been exploring other type of thermoplastic materials to be used as 3D printing filament. This is a promising research area that can be explored. However, turning specific type of waste thermoplastic material into filament to be use for 3D printing filament is not currently available in Sabah. Furthermore, the machine used to produce filament is only available for large or industrial scale, that requires a huge quantities of waste plastic materials. Mini extrusion machine has been developed in the Faculty of Engineering. Initial testing had proven that the machine able to produce filament. However, modification and improvement are needed to ensure the effectiveness and workability of the machine to produce a good filament. One of the extrusion's machine components that needed improvement is the screw. In the initial design, a concrete hammer-drill bit is used, however the depth of the screw (internal screw's diameter) is not deep enough thus do not produce sufficient stress to ensure plastic melting. Due to this, external heater needs to be applied on the external of the barrel. The suitable placement of the heaters along the screw-barrel needs to be investigated systematically, to ensure uniform melting of waste thermoplastic inside the barrel and throughout the extrusion process. Apart from that the effect of extrusion-rate, which is influence by the speed rate of the screw needed to be study to achieve an optimum filament's quality. The filament produce should have a consistent diameter, and suitable porosity, thermal and mechanical properties to be use in 3D printer.

1.3 Research Objective

The main objective of this project is to produce a filament from high density polyethylene (HDPE) waste using a tabletop extrusion machine that priorly custom-made in the Mechanical Engineering Lab, in the FKJ. To successfully achieved a usable 3D printing filament, the following objective need to be identify:

i. The physical properties of produced HDPE filament, which is filament diameter, filament roundness and filament porosity.
ii. The produced HDPE filament's hardness and roughness.

1.4 Scope of Work

This project's scope involves research on previous studies on related topics and fields, which includes the type of materials used for Fused deposition modelling (FDM) 3D printing. The suitability of a drill bit to replace the function of the extrusion screw in this machine must be investigated and assessed by studying previous studies that have used a drill bit as an auger or screw. Besides, modify the previous design of the extrusion machine to produce HDPE filament. Other than that, an experiment to identify the suitable speed and temperature of the extrusion machine to produce a good quality of HDPE filament. The consistency of the extruder machine in producing a filament will be taken into consideration in order to produce a high-quality extruder machine with good performance. The produced filament will be tested to identify the quality of the filament.

1.5 Research Methodology

i. Identifying Problem and Research Study

The project is established by receiving the topic from the supervisor and the problem been identified which is to produce filament from HDPE waste using custom made mini extrusion machine because the PLA or ABS filament is expensive and could not be recycle. The main goals are to produce a good quality of filament from HDPE waste that can be used for 3D printing. The research study was done to make better understanding on this project by surfing through the internet to search for related articles, books, journal, and YouTube to see some experiment related to this project. It includes current information, historical research, and pertinent background, such as the appropriateness of HDPE material as a filament. The background research paints a fuller picture of the project.

ii. Material Selection and Fabrication Process

Material selection for this project is only one which is HDPE waste. To produce the 3D printing filament from HDPE waste.

iii. Prototype testing

The prototype testing will be examined right after the modify of the prototype is done and all the data of HDPE waste characteristics is identified. For this step is to determine whether the project is successful by evaluating the prototype can be working or not as well as to verify that the setting of the prototype have met required technical objectives. The Filament produce will be generally testes in terms of properties that includes its diameter consistency, porosity, thermal and mechanical properties. This test wants to make sure that the filament produces by the prototype is can be use in the 3D printer.

iv. Data Collection and Performance Evaluation

The data collected during prototype testing will be analyzed further to assess the performance of the extrusion machine. It will then be recorded for the calculation of mathematical modelling such as the melt flow rate of the FDM filaments produced by this extrusion machine.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

This part reviewed the background of the extruder machine available commercially. Various approaches, such as reviewing related journals, books, articles, or research journals, are used to identify and consider theoretical information related to design modelling, such as material selection, engineering approaches, and mathematical modelling, that must be considered so that no problems arise if important factors are overlooked at an earlier stage. The criteria include the drill bit's eligibility to become the auger, the temperature distribution along the screw barrel, the qualities of HDPE, and so on. This section will be expanded upon in the subsection that follows.

2.2 Extrusion machine

An extrusion machine is just a device used prior to manufacturing 3D filament with a 3D printer. In other terms, it is a machine that is used to make a spool of filament. Different extruders have different melting temperatures, and it can only be used for the specific type of plastic that is melted using that unique extrusion machine. An extruder designed to make HDPE filament, for example, cannot be used to produce PLA filament since the temperature set by the heating filament is completely different. Extruding is the process of squeezing raw material through a die in a continuous process such that the filament becomes a spool with a consistent diameter. The product is known as extrudate, and it will be utilised to create a 3D item using an FDM 3D printer. Charles Hancock invented the screw-driven extruder machine, which was initially commercialised in the United States around 1870. (Poudel, 2015)

2.2.1 Component & Design of Plastic Extrusion Machine

Figure 2.1 shows the components and design of the extrusion machine in further detail. Most of the image depicts mechanical pieces, with the exception of the band heater, which is included in the portion of the electrical device and will be connected to the other electronic components to activate its desired temperature. It also depicts HDPE pellets as well as the molten plastic stage.

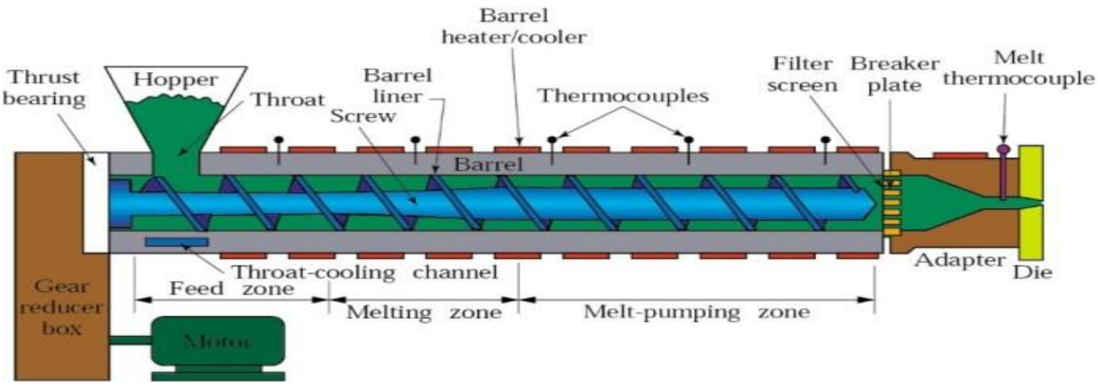

Figure 2.1: Schematic View of Extrusion Machine
Source : Saurabh. (t.th.)

a. Mechanical Parts of the Extruder

<u>Auger (Screw):</u>

This prototype's auger is a drill bit screw instead of an extrusion screw. There has been researched that used a piston, but it is difficult to make filaments of constant thickness using a piston, and air that is present around the granules cannot escape to the surrounding during compression. During extrusion, the screw has a significant impact. Its job is to push granules into the barrel and convey material from the hopper to the system (Poudel, 2015). The screw will be driven by an AC motor and placed inside a screw barrel. If a screw cannot create enough pressure due to flow constraints, or if it generates more pressure than is required, filament quality will be affected, leading to waste and a drop in productivity (García-León *et al.*, 2019). In this project, a drill bit screw with an 18 mm diameter and a 400 mm length will be used in this experiment.

<u>Barrel (Chamber):</u>

A barrel or chamber is a hollow cylindrical pipe that contains the screw. The barrel is a critical component of an extruder machine because it interacts with the screw drill to melt, convey, and exert pressure on the material within the extruder. This interaction must occur under controlled condition (Dynisco, t.th.). The extruder is expected to produce a uniform material, so this mechanism is important. Steel F-174 was chosen for the barrel because it has a high melting point and has a high durability (Woem *et al.*, 2018; Nassar *et al.*, 2019).

Hopper:

Hopper is a component attached to the barrel that allows materials to be fed into the extruder via the hole generated between the hopper and the barrel due to the hopper's gravity fed design. It doesn't matter what size the hopper is as long as the base of the hopper is measured to the holes on the barrel. A metal sheet will be used to make the hopper because there are no specific parameters that need to be considered (Woem *et al.*, 2018; Nassar *et al.*, 2019).

Nozzle:

Since the filament diameter significantly affects the flow rates through an extruder, 1.75 mm filament has greater flexibility than 3.00 filament due to its higher surface area to volume ratio. A die with a hole of 1.75 mm, which is the standard diameter of the filament, will be used to make a hole in the nozzle where the extrudate is made, so this is the diameter that will be used. The narrower the die diameter of the nozzle, the higher the volume extrusion rates. (Paul, 2019)

Motor:

A DC motor or actuator is utilized to rotate the screw drill bit within the barrel. It ensures that the screw rotates with a constant amount of torque. The stepper motor will be used as the DC motor in this project. Utilizing a DC motor in combination with a gearbox or chain system improves the motor's performance by decreasing the load- to-motor inertia ratio, increasing load torque, and reducing the oscillations of the motor (Collins D, 2019).

One of the benefits of using a DC motor for an extrusion machine is that the speed can be changed at any time and corrected as necessary. Therefore, it is possible to perform an efficient operation while also protecting the screw if the beginning speed and torque are adjusted appropriately. This is important because the screw's weakest point is in the hopper area, where the thinnest screw root is located (Dynisco, t.th.). To figure out what speed and torque to use to turn the screw, the diameter of the screw must be known first. The horsepower of a motor can be determined by applying the formula,

$$HP = 6.28 \times rpm \times \frac{torque}{33000} = rpm \times \frac{torque}{5255} \dots (2.1)$$

The rule of thumb theory can be used to estimate the size of the motor needed to rotate the screw, which is approximately 10 lbs/hr is equals to 0.00126 kg/s in SI unit of polymer that can be extruded per horsepower, hp (Dynisco, t.th.). Table 2.1 below shows the power of the motor required by identifying the diameter of the screw.

Table 2.1: The Power of the Motor Needed Based on the Screw Diameter

Diameter (mm)	Power	
	kW	hp
38	12	16
50	40	50
90	85	115
100	130	175
150	230	310
200	400	530

Source: Goff, j. & Whelan, T, (t.th.)

b. Electronic Components

Band Heater:

Band heaters are commonly used in injection moulding and extruder systems, where they are specifically designed to be applied directly to the outside of cylindrical surfaces, such as the barrel in this study, where cylindrical pipe will be used as the housing of the plastic granules. Band heaters have high temperature and watt densities, making them ideal for the extrusion process (Crowther, 1998). Type K Thermocouple will be chosen based on some extruding process properties because it is reliable, has a wide temperature range, and is inexpensive (Abouellai *et al*, 2018).

Thermocouple:

A thermocouple is a type of sensor that detects the temperature of an object. It has two wire legs made of different metals. The electric voltage produced when two materials are heated tells the temperature of the system by reading the temperature changes (Abouellai *et al*, 2018).

PID Controller:

A PID Controller, also known as a temperature controller, is a device used to control the temperature. It is a type of device that sends data to SSR when it is turned on and off (Bennett, 1993).

2.2.2 Working principle of Plastic Extrusion Machine

The working principle of an extruder that has so much in common with injection moulding process will be divided into six different processing steps which is feeding, melt, melt conveying, mixing, De-volatilization and die forming. In general, the extruder component includes a screw, barrel, hopper, heat control unit, and nozzle that is in contact with the die while extruding. The plastic granules will immediately drop into the hopper due to the hopper being designed as gravity fed to the barrel, which contains the rotating screw of the extruder. The motor rotates this screw with constant torque. The rotating screw then propels the plastic granules into a barrel that has been heated to the desired melting temperature (Technology, 2020). Once the plastic granules reach the heating profile, where mostly band heaters are used along with more than one PID controller in charge of controlling the heat zones and gradually increasing the temperature of the barrel, the plastic granules will slowly and gradually melt in the zone and enter the die where the customised final product is produced. Extrusion is a continuous process in which the satisfied product is produced if every step in the filament manufacturing process goes as planned. The control inputs of the extrusion machine, as well as the temperature measurement for required polymers, are critical components that must be in proper working order so that no errors in the final product occur.

2.2.3 Temperature in The Screw Barrel

Knowing the correct temperature profile in the screw barrel is crucial to ensuring that the material in the form of flakes is melted down with progressive temperature at different zones of the extrusion screw. The temperature profiles of different types of polyethene are shown in Table 2.2: Low Density Polyethylene (LDPE), Linear Low-Density Polyethylene (LLDPE), and High-Density Polyethylene (HDPE). The temperature barrels shown are categorised by material, which means that the temperature that should be set depends on the material used for the extrusion machine.