EFFECT OF FUSED DEPOSITION MODELING (FDM) PARAMETERS ON THE WARPAGE AND DIFFERENT COMPOSITION POLYLACTIC ACID/ETHYLENE-VINYL ACETATE BLEND

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Declaration

I hereby declare that I have conducted, completed the research work and written the dissertation entitled **'Effect of FDM parameters on different composition Polylactic Acid/Ethylene-Vinyl Acetate Blend'**. I also declared that it has not been previously submitted for the award for any degree or diploma of other similar title of this for any other examining body or University.

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Witness by

Supervisor: Dr. Arjulizan Rusli Signature:

Date: 11/8/2022

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LIST OF ABBREVIATIONS

Abbreviation	Description
T_{cc}	Cold Crystallization temperature
T_g	Glass Transition Temperature
T_m	Melting Temperature
3D	Three-dimensional
ABS	Acrylonitrile-butadiene-styrene
AM	Additive manufacturing
CAD	Computer-aided design
CT	Computer Tomography
DSC	Differential Scanning Calorimetry
EGMA	Poly(ethylene-co-glycidyl methacrylate)
EVA	Ethylene vinyl acetate
FDM	Fused deposition modelling
HDT	Heat Deflection Temperature
MFI	Melt Flow Index
PBAT	Poly(butylene adipate-co-terephthalate)
PBS	Poly(butylene succinate)
PCL	Poly(caprolactone)
PET	Poly (ethylene terephthalate)
PHAs	Poly(hydroxyalkanoate)s
PLA	Polylactic acid
PS	Polystyrene
SEM	Scanning electron microscopy

STL	Standard Tessellation Language
VAc	Vinyl acetate

ABSTRAK

KESAN PARAMETER PEMODELAN ENDAPAN TERLAKUR (FDM) TERHADAP PENGGELEDINGAN DAN CAMPURAN POLI (ASID LAKTIK)/ETILENE-VINYL ASETAT BERBEZA KOMPOSISI

Pemodelan Endapan Terlakur (FDM) ialah kaedah pencetakan 3D yang popular untuk mencipta objek dengan reka bentuk yang rumit dan berkos rendah. Isu yang biasa berlaku semasa proses pencetakan FDM ialah penggeledingan objek yang menyumbang kepada kekurangan sifat mekanikal dan juga mengurangkan ketepatan dimensi. Penyelidikan ini bertujuan untuk menyiasat kesan parameter pemprosesan FDM iaitu suhu lantai dan kelajuan cetakan ke atas ledingan bahagian bercetak yang dihasilkan daripada campuran poli asid laktik tulen (PLA) dan PLA/etilena vinil asetat (EVA). Campuran PLA/EVA disediakan secara pracampuran dengan menggunakan adunan dalaman manakala filamen dihasilkan dengan menggunakan penyemperit skru tunggal. Kajian mengenai ledingan bahagian yang dicetak pada suhu lantai yang berbeza (50, 70 dan 90°C) telah menunjukkan bahawa ledingan PLA tulen berkurangan dengan peningkatan suhu lantai manakala tren berlawanan dapat diperhatikan dalam adunan disebabkan oleh keupayaan adunan untuk menghablur lebih tinggi apabila dicetak pada suhu yang lebih tinggi. Suhu pada 50°C dianggap sebagai suhu lantai terbaik untuk mengurangkan ledingan adunan. Sementara itu, PLA tulen dan adunan bahagian yang dicetak pada kelajuan cetakan berbeza (10, 35 dan 70mm/s) telah menunjukkan ledingan terendah apabila dicetak pada 10mm/s. Perbandingan sifat tegangan bagi sampel acuan mampatan dan sampel yang dihasilkan daripada FDM menunjukkan pengurangan tegangan dan modulus yang sama dengan peningkatan kandungan EVA tetapi nilai yang lebih rendah untuk sampel cetakan 3D. Walau bagaimanapun, sampel

cetakan 3D yang dibuat daripada adunan dengan 10wt% EVA dalam PLA menunjukkan pemanjangan takat putus yang lebih tinggi berbanding dengan sampel acuan mampatan yang menunjukkan kekukuhan yang lebih baik daripada sampel yang terdahulu disebabkan interaksi antara fasa yang lebih baik antara EVA dan PLA.

ABSTRACT

EFFECT OF FUSED DEPOSITION MODELLING (FDM) PARAMETERS ON THE WARPAGE AND DIFFERENT COMPOSITION POLYLACTIC ACID/ETHYLENE-VINYL ACETATE BLEND

Fused Deposition Modelling (FDM) is a popular 3D printing method to create a part with complicated design and low cost. A common issue that occurs during FDM printing process is the warpage of the part which contributes to inadequate mechanical properties and reduced dimensional accuracy. This research aims to investigate the effect FDM processing parameters i.e bed temperature and printing speed on the warpage of printed parts produced from fabricated pure polylactic acid (PLA) and PLA/ethylene vinyl acetate (EVA) blend. The PLA/EVA blends were prepared by premixing using an internal mixing while filaments were fabricated using a single screw extruder. Study on the warpage of parts printed at different bed temperatures (50, 70 and 90°C) indicated that the warpage of pure PLA reduced with increasing bed temperature while a reverse trend was observed in blends due to a higher ability to crystallize in the former when printed at a higher temperature. Temperature at 50°C is considered the best bed temperature for reducing the warpage of the blends. Meanwhile, pure PLA and blends parts printed at different printing speeds (10, 35 and 70mm/s) indicated the lowest warpage when printed at 10mm/s. Comparison of tensile properties of compression moulded samples and samples produced from FDM showed similar reduction of tensile and modulus with increasing EVA content but lower values for 3D printed samples. However, 3D printed samples made from blends with 10wt% EVA in PLA indicated higher elongation at break compared with compression moulded samples

suggesting better toughness of the former due to better interphase interaction between EVA and PLA.

CHAPTER 1

INTRODUCTION

1.1.1 Background

Fused deposition modelling (FDM) is one of the production technique in 3D printing. It can produce products with a variety of complicated forms and shapes while effectively handling the resources, leading in reduced waste and a range of additional advantages over traditional production. The FDM manufacturing process is based on the melting and bonding of thermoplastic materials, with polymers functioning as the printing material.

A FDM 3D printing involves several factors and complicated processes such as bed temperature and printing speed have an impact on product quality and material qualities. The combination of parameters setting is very challenging to produce the desired product properties. The optimal parameter setting is thought to increase the quality of 3D printed products and may decrease post-production effort. The print parameter combination on the FDM machine is determined by the kind of filament used in the FDM process. As a result, it is critical to investigate the influence of parameter selection on the mechanical performance of the printed part.

The thermoplastics are the most common materials used in FDM. The material is coiled into a roll, pulled by a winding wheel, and then moved to a nozzle head where it is extruded by heating it to a semiliquid phase. Since FDM designs are created from layers of fine filament, the thermoplasticity of the filament material is important in this method, determining the ability of filaments to form bonding between layers during printing and then solidify at ambient temperature after printing (Kristiawan et al., 2021).

However, one of the significant disadvantages of this method is that the FDM components have lower strength and stiffness than a continuous specimen composed of the same polymer fabricated by traditional processing, for instance injection moulding (Lee et al., 2007). As a result, it is vital to assess how processing settings affect the mechanical properties of 3D printed items.

Polylactic Acid (PLA) is one of the most commonly used material in 3D printing, especially FDM. PLA filaments are an excellent starting point for 3D printing since they are simple to use and have less distortion. Being a biodegradable and renewable thermoplastic polyester, together with its excellent mechanical strength and processability, PLA filament is showing a favourable development when compared to Acrylonitrile butadiene styrene (ABS). The low thermal distortion temperature, brittleness, and slow crystallisation rate of PLA, on the other side, limit its practical applicability in several fields. Despite having similar tensile strength and elastic modulus to poly (ethylene terephthalate) (PET) and polystyrene (PS), PLA's weak toughness limits its application in a variety of industrial and medical applications requiring plastic deformation at high level of stress after printing (Zhao et al., 2020).

PLA's rigid and brittle mechanical features hinder its evolution and application in practice; hence, copolymerization, plasticization, and polymer blending are among of the improvements recommended to enhance its processing and mechanical qualities. Melt blending of polymers is a far more cost-effective and time-efficient way than producing new polymers to obtain features that are not compatible with current polymers (Liu & Zhang, 2011).

Polymer blending is a practical way for the development of new polymeric materials that can produce materials with superior property profiles to those of the individual components since it is generally less expensive and time-consuming than developing new monomers and polymerization processes. Another benefit of polymer blends is that their qualities may be modified by mixing component polymers and modifying the blend ratio (Osman et al., 2018).

PLA has been mixed with various polymers, including poly(caprolactone) (PCL), poly(hydroxyalkanoates) (PHAs), poly(ethylene-co-glycidyl methacrylate) (EGMA), poly(butylene adipate-co-terephthalate) (PBAT), poly(butylene succinate) (PBS), and poly(butylene succinate) (PBS) (ethylene-co-octene) (Sangeetha et al., 2018).

Ethylene vinyl acetate (EVA) is a potentially suitable copolymer with the PLA matrix. EVA has a strong impact strength, which balances for PLA's poor impact strength. EVA is a petroleum-based material with strong impact strength and outstanding processability. EVA is widely utilised to overcome for PLA's poor impact strength and processing issues.

The rubbery and resin characteristics of the EVA co-polymer are believed to be crucial for increasing the toughening capabilities of PLA. Logically, if PLA and the chosen copolymer have a strong interfacial adhesion, the toughening capabilities of PLA can be improved. The impact strength for PLA-EVA blend was reported to grow significantly (176%) with 15wt% of EVA compared to neat PLA because of the strong interfacial adhesion of the PLA matrix and EVA (Sangeetha et al., 2018).

At low EVA concentration, the EVA domain acts as a reinforcing agent in the PLA matrix (5-10wt percent). Kelkar and Kadam (2014), investigated the influence of EVA loading on the strengthen of poly (lactic acid) by EVA copolymer with an 18% vinyl acetate content. PLA/EVA blends of various compositions were successfully created and analysed, with the intention of minimizing the brittleness of PLA and making it easier to handle (Sangeetha et al., 2018).

However, there is a limitation of study on the use of PLA/EVA blend filaments in FDM-based 3D printing technology, as well as on the basic preparation techniques for obtaining PLA blend filaments, which will be utilised as a feedstock in 3D printers.

1.2 Problem Statement

In the case of PLA and EVA copolymer blend, properties are very much affected by the composition of the components. The mechanical characteristics of the PLA-EVA blend exhibited the greatest tensile and flexural strength at 10% EVA loading. When EVA was increased, tensile strength and flexural strength improved. So that the optimal tensile and flexural value for ratio blends was 90PLA/10EVA (Abdul Manan & Mohamad, 2014). It was also discovered that the compatibility with PLA increases with the amount of vinyl acetate (VA) in the PLA matrix. According to Sangeetha et al. (2018a), SEM images revealed a greater particle size distribution in proportion to the EVA weight loading in the PLA matrix. Combination of EVA elastomers with PLA resulting in lower heat stability of PLA with a decrement in T_{onset} and T_{max} degradation temperatures.

Furthermore, extending FDM technique to semi-crystalline polymers has proven difficult due to crystallization upon cooling, which causes FDM part warpage. Furthermore, some unusual occurrences that can occur during the printing of semi-crystalline input filaments and have been found to have a significant influence on the printing process. Examples include self-nucleation as a result of inadequate heat transfer and melting, flow-induced crystallisation as a result of high shear deformations during extrusion, and the adverse effects of crystallisation on mobility of chain, which is useful for the formation of interlayer strength and dimensional accuracy as a result of excessive shrinkage. Crystallization of the extruded polymer melt during deposition from the print nozzle causes anisotropic shrinkage and component warpage due to internal stress build-up. This can have a major influence on the printed part's dimensional stability.

The modification of the FDM samples' bed temperature has a major effect on their degree of crystallinity obtained, cold crystallisation, and melting point. For PLA, it was found that warming up the printing bed slightly over the T_g of the filament feedstock results in optimum adherence of the produced parts to the printing bed. Rising the temperature beyond the filament's T_g promotes drop-in surface tension between the printing bed and the printing material, as well as a greater contact area, which results in improved bed-to-filament adhesion (Spoerk et al., 2018). In addition to bed temperature, according to Goyanes et al. (2014), the printing speeds of a FDM can have an impact on the quality of the manufactured objects. The rate at which the molten polymer is extruded and deposited is referred as the print speed. To ensure complete melting of the previously deposited filament, each increase in printing speed should need an increase in the specified nozzle temperature.

Sangeetha et al. (2016), reported the thermal and mechanical characteristics of PLA-EVA blends with varied EVA comprising 40% vinyl acetate (VA) content. Meanwhile, thermal study revealed that the presence of greater EVA improved crystallinity. Impact strength and elongation at break reduced in the presence of percent EVA due to full phase separation and the production of EVA globules in the PLA continuous phase. Variations in rheological qualities are caused by changes in compatibility and morphology.

1.3 Objectives

The main purpose of this research is to investigate the effect of the printing parameters of FDM on the properties of the PLA/EVA extruded, with specific research objectives are as follows:

i. To examine the effect of compression moulding and extrusion process on the morphological and thermal properties of pure PLA and PLA/EVA blends.

ii. To evaluate the effect of various bed temperature and printing speeds of FDM process on warpage, thermal properties and morphology of pure PLA and PLA blend parts.

iii. To determine the tensile properties of pure PLA and PLA blends where it was printed at an optimized bed temperature and printing speed in comparison with compression moulded samples.

1.4 Thesis Outline

The five chapters of this thesis are as follow:

Chapter 1: Introduction to the research background, problem statement, research objectives and thesis outline.

Chapter 2: Literature reviews on the additive manufacturing (AM), FDM, the effects of FDM printing parameters, warpage and shrinkage in FDM products, the common materials used in FDM and lastly on the PLA/EVA blends.

Chapter 3: Explanation on the details of the raw materials, instruments and software, sample preparation, characterization and the overall research flow chart involved in this research.

Chapter 4: Detailed discussion of the experimental data and results obtained.

Chapter 5: Conclusion and recommendations in this research.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction to Additive Manufacturing

Additive manufacturing (AM) is a collection of manufacturing processes that generate 3D models from digital files by utilizing various apparatus and technology that create products layer by layer. It enables to produce the lighter, stronger parts and systems, which is a transformative approach to industrial production. Additive manufacturing use computer-aided-design (CAD) software data to give command to the machines to deposit material in accurate geometric designs, layer by layer. The versatility of the AM process enables the creation of extremely sophisticated structures that would be impossible to create with any other available technology (Prakash et al., 2017).

AM is also offer a technology for synthesizing materials via fusing, binding, or hardening components such as powders and liquid resin. AM machines are classed based on machine size, nozzle size, nozzle speed, and workspace dimensions. It may be classified in a variety of ways based on its practical framework. The processes of AM can be summarised and classed generally according on the material utilised (Abdulhameed et al., 2019).

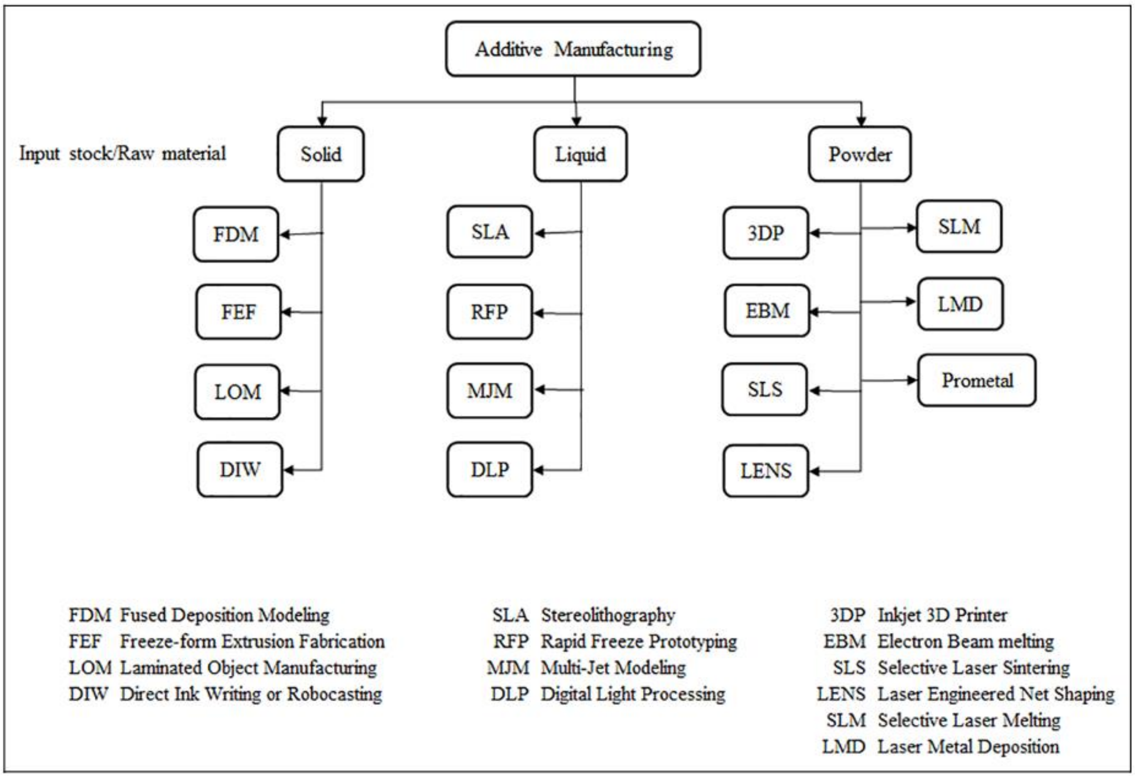

Figure 2.1 Classification of AM processes depending on the state of raw material (Abdulhameed et al., 2019)

3D printing is merely one stage in the total workflow of AM. The approach to additive manufacturing techniques develops an organised flow, depending on various tools to generate processing files for further printing and post-processing. The additive manufacturing process has five essential steps, which are mentioned below and illustrated in Figure 2.2.

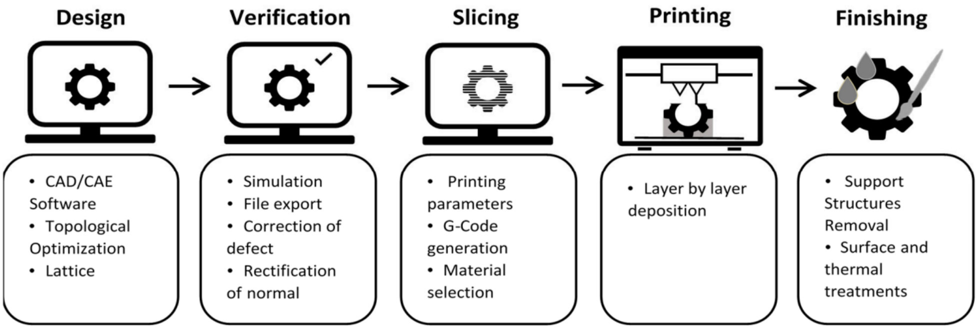

Figure 2.2 Additive manufacturing (AM) workflow (Moreno Nieto et al., 2021)

First, the design of the products that will be generated by additive processes by using CAD software. Because the part is a reproduction of the 3D model, every detail must be precise and its external geometry must be properly described. Although additive manufacturing can print complicated parts and provides the product designer with greater design flexibility than traditional manufacturing techniques, there are still restrictions and rules to follow when designing for the best outcomes. Computer simulation, generative design and topology optimization can all be applied to optimize the function of the part (Ngo et al., 2018). Printing process and material selection usually occurs in this initial design step.

Once the design process is complete, the files must be exported to 3D printing standards, which file format is STL. The fundamental purpose of the STL file format is to represent the surface geometry of a 3D object. However, the initial step of surface verification is recommended because discontinuities or incorrect normal orientations that define the surface triangles may occur (Mwema & Akinlabi, 2020).

Slicing is the process of transforming a three-dimensional model into a set of instructions for three-dimensional printers. A slicer programme turns a 3D CAD model, which is often an STL format file, into g-code, which delivers commands to the printer. It is critical to specify the right process parameters based on the design and material characteristics. Most procedures share the same parameters: height of layer, production rate, temperature, and filling density. The machine path files produced by this process specification are transmitted to the printing equipment for process activation. Slicer parameters that will have a direct influence on the 3D print quality of the models (Maunica Kolla, 2021).

3D printing is a basic physical process in which items are materialised using 3D printers by placing melted material layer upon layer, with thermoplastic polymers as feedstock. When compared to typical production methods such as injection moulding, all of these technologies have one thing in common: they are lengthy and require post-processing. The only considerations are filament type, filament supply, utilising the appropriate nozzle for the filament and temperature range, and proper calibration.

Depends on the parameters of the process, intervention is required to get the desired finish and features of the printed components. Post-processing a 3D printed part includes three main steps: support removal, surface finish and dyeing. In the case of printing prototypes, manual post processing is usually sufficient, regardless of the printing technology being used. But when it comes to manufacturing applications that require high volumes, automated solutions offer real value and help to streamline the whole process (Dizon et al. 2021).

2.2 Fused Deposition Modelling (FDM)

Fused deposition modelling (FDM), a type of techniques used in 3D printing under the additive manufacturing engineering class. FDM 3D printing technology enables the manufacture of complicated and detailed items. Therefore, engineers are utilising it to test parts for fit and form. FDM can handle materials effectively, resulting in reduced waste and a variety of additional advantages over traditional production methods such as injection moulding. In terms of production, FDM plays a similar function to injection moulding, but without the added expenditures of creating moulds and equipment for customised products (Kristiawan et al., 2021).

The fundamental concept of the FDM process includes the use of thermoplastic material that melts, then pressed out in layers to make a 3D object. The feedstock is a filament placed in a roll, drawn by a drive wheel, and then direct into a nozzle head. The filament in nozzle is heated into semi-liquid and precisely extrudes and guides materials on platform to produce layer by layer structural elements. This follows the contours of the layer defined by the application, which is often CAD and has been incorporated into the FDM work system (Kristiawan et al., 2021).

The modesty of the process, high-speed printing, and low cost make FDM become more popular in manufacturing technique. The drawbacks of the FDM technology include process parameter-dependent mechanical characteristics and FDM printing materials that are limited to thermoplastic polymers due to thermoplasticity which is required for a material to be 3D printed using the FDM method (Ngo et al., 2018). The quality and mechanical properties of FDM printed items are largely determined by the correct selection of process settings.

The key benefits of FDM method, it is a easier manufacturing process and more cost-effective way in contrast to other popular 3D printing processes. In addition, it can nevertheless produce complicated shapes and cavities with good dimensional precision. One of the main advantages of using the FDM method is its compatibility with a wide range of thermoplastic polymers. The amorphous polymer such as ABS is still not advised for mechanically significant components, where high stiffness and strength are crucial. Instead, it is typically used for prototypes (Rahim et al., 2019).

Nevertheless, there are certain problems that have discovered, mainly in regard to the poorer mechanical qualities presented in FDM components when compared to the parts manufactured by traditional methods like injection and compression methods. The reason is that FDM products always have considerable void formation, whereas compression and injection moulded parts have nearly no apparent void content (Rahim et al., 2019).

Goh et al. (2018), performed X-ray CT scanning of FDM-printed objects, revealing the existence of many interior pores generated during the printing process. Additionally, delamination and reduced mechanical integrity may result from temperature changes on the layers. The printed components exhibit anisotropic behaviour as a result of the process' variation in build direction or raster orientation, resulting in weak sections that are perpendicular to the created axis.

Because FDM forms are formed from layers of thin filament, there are numerous features of polymers that can contribute to how efficiently the part prints and the final qualities of the printed parts when selecting a thermoplastic polymer to utilise in an FDM. According to Bates-Green & Howie (2017), melting temperature (T_m) and glass transition temperature (T_g) are important variables to consider when determining how effectively a polymer prints. The melting temperature will give influence to temperature the extruder needs to be at to print the polymer. T_g of a material relates to the thermal stress developed during printing which can affect bed adhesion (Bates-Green & Howie, 2017).

A few FDM processing settings impact the mechanical qualities of the printed item. The complicated needs of FDM made material creation for the filament a difficult process. As a result, determining the optimal process parameter combination to increase component quality and mechanical qualities becomes critical in order to make FDM appropriate for mass production and more desirable by industries.

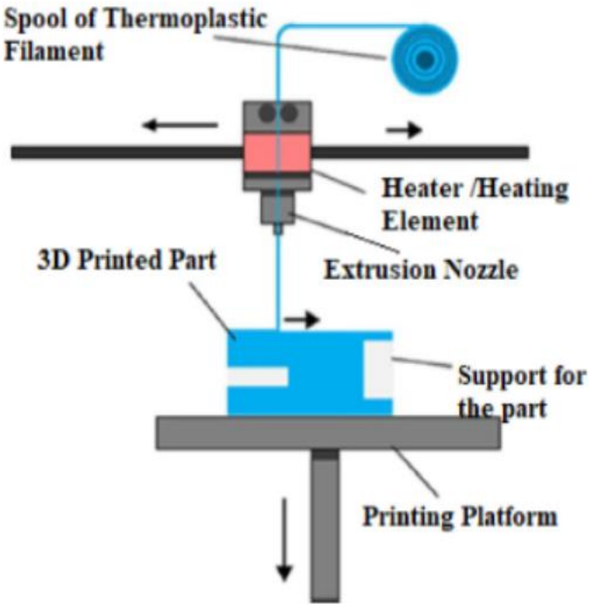

Figure 2.3 Setup of FDM process (Jaisingh Sheoran & Kumar, 2020).

As illustrated in Figure 2.3, after a continuous supply of material filament is available, it is heated to a semi-liquid phase by the heating element within the liquefying head, and this semi-liquid thermoplastic is extruded through the extrusion nozzle on the printing bed/platform. The main functional concept of FDM is that the semi-liquid thermoplastic filament materials do not solidify immediately when extruded from the nozzle on the printing platform, but instead fuse together before curing/ solidifying into a layer-wise stacked part in the surrounding ambient temperature.

2.3 Parameters of FDM

There are various process factors in the FDM process, and they have a substantial influence on production efficiency and product properties. The main process parameters are described accordingly. Several criteria have a significant influence on the building part qualities and manufacturing efficiency. Some of the most important characteristics include layer thickness, raster angle, build orientation, infill density, printing speed, infill pattern, extrusion temperature, raster width, nozzle diameter, contour width, contour to contour air gap, contours numbers, air gap, and so on (Gao et al., 2022). Because of the importance of these factors on the part characteristics, many research have been done on investigating the effect of these parameters on various characteristics and properties of FDM printed parts.

Researchers must optimise any manufacturing process to provide a high-quality end product in terms of dimensional accuracy and mechanical qualities. Table 2.1 use a comprehensive assessment of several studies on the optimization of FDM process settings along with their description.

Table 2.1 Different FDM process settings and its description (Jaisingh Sheoran & Kumar, 2020)

No.	FDM process parameters	Description
1.	Layer thickness	The height of layers deposited after extrusion from nozzle tip measured along Z-direction of the FDM machine.
2.	Build Orientation	Orientation of part within the build platform with respect to directions of the FDM machine and also the angle at which the part would be printed.
3.	Raster Angle	It is the angle with respect to X-direction of build platform, in which extruded material is deposited.
4.	Air gap	The distance between 2 adjacent tool paths (or rasters) on a single layer of the FDM printed part.
5.	Extrusion temperature	The temperature to which the thermoplastic filament materials heated inside the nozzle before extrusion in the FDM process.
6.	Nozzle diameter	Diameter of nozzle tip of the extruder.
7.	Raster width	Width of the beads deposited along the extruder tool path (which forms the raster). It depends mainly on the diameter of the extruder nozzle tip.
8.	Number of contours	Number of solid outer layers, that surrounds the internal infill pattern of the FDM printed part.
9.	Contour width	The thickness of the outer layers (contour layers) surrounding the internal structure.
10.	Contour to contour Air gap	It is the distance or air gap between the solid outer layers (or contours)
11.	Print Speed	The speed of the traveling nozzle tip for depositing material.
12.	Infill pattern	The pattern in which material is deposited to form the internal structure of the FDM printed part is the infill pattern.
13.	Infill density	Implies the solidity of the internal structure of the FDM printed part.

2.4 Bed Temperature

Due to the temperature range of the melt and bed was quite wide, variations in these parameters resulted in differences in the degree of filling of the final sample models. According to Rosli et al., (2020), there are deformation of an ABS warpage sample with varied bed temperatures. They discovered that the higher bed temperature resulted in a smaller warpage of the ABS sample due to a greater capacity to release thermal stress when cooled to a higher bed temperature which has slow cooling rate. Xinhua et al. (2015) also found warpage at the corner of a thin section in PLA samples at varied printing parameters.

Meanwhile, Choi et al., (2016) showed that shrinkage of the ABS material getting increased when the temperature of the bed was much lower than 40℃ due to inadequate interlayer adhesion. When the bed temperature was set at 90℃, as contrast to 110℃, the inaccuracies shape caused by thermal shrinkage rose dramatically. Given that the ABS softness point is 104℃, the bed temperature of 110℃, which is almost identical to the ABS softening point, created a small thermal gradient between the ABS material and the bed during the AM, resulting in low heat shrinkage. When the bed temperature was far lower than the softening point, the considerable thermal differential between the ABS material and the bed during the AM appeared to significantly increase heat shrinkage (Choi et al., 2016).

The investigation of the effect on mechanical properties of PLA by altering the temperature of the printing process in carried out by Benwood et al., (2018). In their study, different bed and melting temperatures were used to print samples and impact test was conducted for strength. They discovered that materials printed at high bed and melting temperatures had decreased porosity and enhancing density and crystallinity. As a result, print settings were crucial role in optimising the mechanical characteristics of PLA. The interlayer adhesion of PLA parts is influenced by both the bed and nozzle temperatures.

The thermal differential between the nozzle and the bed temperature influenced the adhesion strength. The layer-to-layer contact temperature rose as bed temperature increased. As a result, intermolecular diffusion and high interfacial adhesion were dominant (Kasmi et al., 2021a). Behzadnasab and Yousefi discovered that when the set nozzle temperature went to 240 °C, the strength of a PLA 3D printed part improved. However, a higher nozzle temperature more than 240 °C resulted in polymer degradation.

2.5 Printing Speed

According to Goyanes et al. (2014), the printing speed of a 3D printing process might alter the grade of the manufactured products. Printing speed is the speed at which the printing head moves, which influences the cross-section form of the deposited filaments. Higher printing speeds result in a shorter forming period, which reduces the strength of printed specimens.

Furthermore, the printing speed has an evident impact on the mechanical qualities of the printed pieces. A high printing speed might cause poor layer bonding and, as a result, a loss in the mechanical strength of the product. Generally, printing speed can have a major effect on a material's cooling rate and melting rate, yielding poor layer bonding (Abeykoon et al., 2020).

It can be expected because polymers are poor heat conductors, high speeds are likely to impact the melting of the filament, resulting in poor adhesion between neighbouring layers and particles, and hence a decreased strength. As a result, to minimise melting instabilities, the selected nozzle temperature and printing speed should be suitable. That is, if the temperature is set too high at moderate rates, the melt becomes less viscous, affecting the dimensional stability of the pieces as well as the cooling time necessary. Similarly, too low temperature at high speeds, the filament may not melt at an appropriate rate (due to materials becoming trapped within the nozzle) and the melt may be more viscous than it should be (Abeykoon et al., 2020).

According to Rezaeian et al. (2022), a slower printing speed causes more crystallisation in the material, resulting in stronger strength and poorer ductility. Aside from how printing speed affects the bulk material, the microstructure of FDM specimens that have been manufactured can have an impact on their overall performance. In general, speeding up printing can lessen the temperature disparity between the first and last layers. Because of the greater average temperature during printing due to the reduced thermal gradient, it may be easier for the molten filament to enter the air gaps during the deposition process.

Nabavi-Kivi et al. (2022), stated that higher printing rates can be beyond the capabilities of FDM machines, which would lead to inappropriate raster deposition. The temperature differential between the layers deposited is expected to be reduced at greater printing rates, resulting in improved layer adhesion. Slower printing resulted in each printed layer being deposited on the previously printed layer at a lower temperature, resulting in a larger temperature differential.

2.6 Filament Material

For the FDM method, several thermoplastic materials are accessible in the form of filament. Filament extruders, such as single screw extruders, are used to make thermoplastic and composite filaments. Plastics extrusion using a single screw is a high-volume production method. It melts thermoplastic materials to create a continuous profile. The extrusion process begins with the insertion of plastic ingredients in the barrel through the hopper. The thermoplastic ingredients are homogeneously mixed and melted as a result of a thermistor mounted on the barrel's surface and mechanical energy created by twisting the screw. When molten plastic is fed through a die, the die moulds the liquid plastic into a desired form that solidifies after cooling (Penumakala et al., 2020).

In the filament production process, raw materials in the form of granulates or pellets are fed into the barrel through a hopper. The raw ingredients are heated in the barrel, which also serves as the rotating screw's housing (s). The barrel is divided into three zones: the feed zone, the transition zone, and the metering zone. In the feed zone, the raw materials soften, plasticize in the transition zone, and totally melt in the metering zone. Temperatures in different zones are chosen based on the materials used. The input materials flow through the rotating screw's surface from the feed zone to the transition zone and finally to the metering zone. From the metering zone, the melted raw materials are extruded via a die. The die diameter is determined by the desired filament diameter. For FDM printing, 1.75 mm ±0.05 mm tolerance filaments are required to carry out the printing process. After passing through the die, the extruded materials pass through a cooling zone. A filament extruder is shown in Figure 2.4 (Penumakala et al., 2020).

Furthermore, the filament must have a diameter of 1.75 ± 0.03 mm to be utilized in the FDM process. A single screw extruder is used to produce a long filament to be used in FDM. However, there will be a diameter discrepancy between the die and the fabricated filament due to the die swell phenomena that commonly happen during polymer extrusion. To obtain a consistent diameter and minimize the variation of diameter of filaments, processing parameters such as screw speed, winding speed, and temperature must be carefully selected and modified until an ideal diameter of 1.75 mm for the filament is obtained.

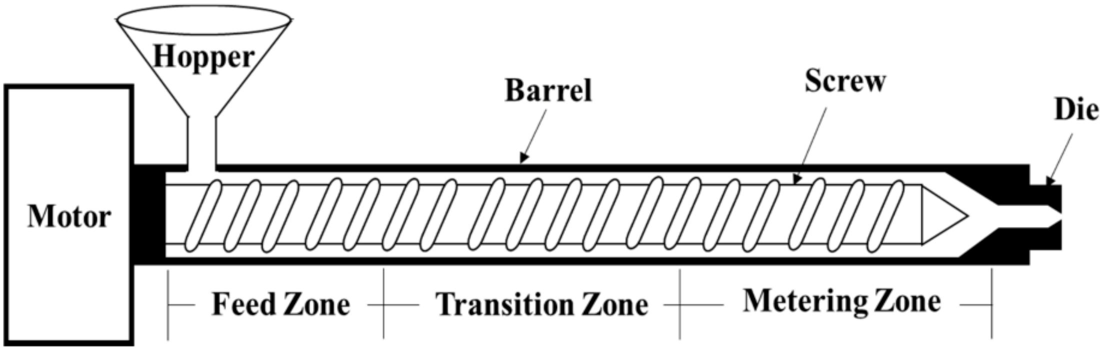

Figure 2.4 A layout of filament fabrication extruder (Penumakala et al., 2020).

2.7 PLA

Because of its biodegradability and ecologically favourable qualities PLA is the most often used raw material in the FDM-based 3D printing method. However, the use of pure PLA polymer is constrained in the FDM method because of its drawbacks, including mechanical brittleness and a high rate of water solubility. As a result, it is recommended that making PLA composites with the right additives is a workable way to enhance the qualities of PLA components produced using 3D printing and FDM (Tümer & Erbil, 2021).

Commonly used 3D printing polymers, PLA can degrade significantly when exposed to high temperatures and moisture over lengthy periods of time. Because of its methyl side groups, PLA is mostly hydrophobic. If PLA is not adequately dried before processing, the molecular weight reduction will be substantial, affecting the end-product quality. PLA should be dried in oven overnight before melt blending in internal mixer.

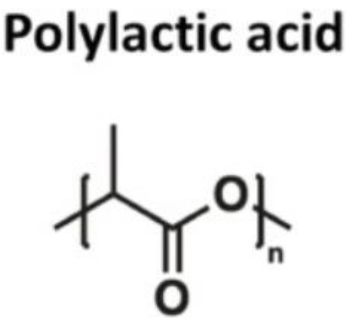

Figure 2.5 Chemical structure of PLA

PLA material has gone mainstream in 3D printing due to its superior material properties, high reliability, low cost, dimensional precision, and surface polish, as well as its use of renewable resources. It is simple to print and strong, but it is more brittle than other 3D printer materials such as ABS (Naveed, 2021). PLA has several advantages, including high mechanical strength, good biodegradability, and thermal flexibility, but it also has substantial limitations, including low impact strength, poor toughness, great vulnerability to environmental stress, and brittleness. These drawbacks can be overcome by employing co-polymerization, plasticization, and mixing techniques with suitable elastomers (Ma et al., 2012).

Liao et al. (2019) stated that the 3D printing behaviour of pure PLA is still cannot be well controlled due to its complex crystallization behaviour. The properties of polylactic acid (PLA) filaments are strongly affected by the extrusion process used in some additive manufacturing systems. Many PLA variants with varying isomer ratios may be generated, and the thermal, mechanical, and biodegradation properties of PLA are depending on the stereoisomer distribution within the polymer chains. For example, when the D-content exceeds 20%, a totally amorphous polymer may be formed, but highly crystalline PLA can only be obtained when the L-content exceeds 90% (Tümer & Erbil, 2021).

Semi crystalline PLA has a melting temperature in the range of 170–180 °C and glass transition temperature (T_g) around 60 °C. Semi-crystalline PLA crystallisation is quite extremely slow. As a result, achieving high crystallinity without changing the formulation is challenging. In the conditions of heat deflection temperature (HDT), increasing the crystallisation rate of PLA is critical because more crystalline form leads to high HDT at service temperatures over T_g (Farah et al., 2016).

Semi-crystalline polymers vary from their amorphous counterparts due to the production of tightly packed and organised crystalline areas. Because of their crystalline structure, semi-crystalline polymers are often opaque. PLA polymers are classified as amorphous glassy polymers, semi-crystalline polymers, and highly crystalline polymers, exhibiting mechanical qualities that are significantly dependent on crystallinity. The crystalline zones provide increased toughness and abrasion resistance, as well as stiffness and strength. Contrarily, amorphous thermoplastics soften slowly when heated above the material's T_g, semi-crystalline polymers' crystals remain orderly packed until their melting point, at which they transformed to the liquid state (Vaes & van Puyvelde, 2021).

Because polymer chains are packed closely in these crystalline areas, the density of semi-crystalline polymers increases. However, due to the dense packing that occurs during crystallisation, semi-crystalline thermoplastics gave more shrinkage upon cooling than amorphous polymers (Vaes & van Puyvelde, 2021).

2.8 PLA/EVA blends

Blending with flexible or soft polymers is an effective strategy for PLA development. One of the polymers commonly referred to as expanded rubber is ethylene-vinyl acetate (EVA). Its foams are commonly utilised as shock absorbers in athletic shoes. EVA is a copolymer of ethylene and vinyl acetate, with the percentage of vinyl acetate varying between 10% and 40%. As the number of polar vinyl acetate groups increases, the products transition from modified polyethylene to rubber-like polymers (Han et al., 2020). EVA, in contrast to PLA, is best known for its flexibility and toughness even at low temperatures, adhesive properties, and stress-cracking resistance.

Its features are linked with its complex structural, which is composed of three phases: crystalline ethylene segments, an interfacial region composed of ethylene and vinyl acetate segments, and a complex amorphous phase composed of crystalline ethylene segments and non-crystallized VAc segments (Singla et al., 2017). Because of EVA copolymer's key rubber and resin qualities, it may be combined with other thermoplastic polymers for a variety of applications.

PLA has been used with EVA to boost its properties. According to Sangeetha et al. (2018), the impact strength of PLA-EVA blends increases by 176 % for 15wt % EVA loading compared to neat PLA. This is because PLA and EVA have significant interfacial adhesion, resulting in a brittle to ductile transition. The toughening effect of PLA by EVA was suggested by SEM study of freezed fractured surfaces of PLA blends. When compared to neat PLA, DSC studies for PLA/EVA blends demonstrated an enhancement in crystallinity. DSC was used to investigate the influence of EVA on the non-isothermal melt crystallisation kinetics of PLA at various heating rates. The decreasing trend in $T\frac{1}{2}$ values showed a quicker crystallisation process after the addition of EVA elastomers to the PLA matrix (Sangeetha et al., 2018).

Moradi and Yeganeh, (2020) stated that according to SEM images, The blend had a well-defined interface, large EVA globules, and voids generated by interfacial debonding. DSC experiments revealed that combining PLA with EVA may significantly lower PLA crystallisation from 30.21 % to 16.26 cent, as well as raise the cold crystallisation temperature.

2.9 Summary

There is large number of researches has been done on PLA/EVA blend for properties improvement of PLA in terms of reduction of the brittleness. However, not much research has been carried out on the fabrication of filament from PLA/EVA blends for the 3D printing application. The properties such as thermal properties, morphological properties and mechanical properties of PLA-EVA blend before and after 3d printing should be tested to investigate it possible usage for the new application. In addition, the warpage of pure PLA and PLA/EVA blend printed at different bed temperatures and print speed should be evaluated to examine the influence of those processing settings on the properties and dimensional stability of the parts.