STUDY OF MELTING OF LOW TEMPERATURE METAL FOR FUSED FILAMENT FABRICATION (FFF) PROCESS

ONG TUN YAU

FACULTY OF ENGINEERING

UNIVERSITI MALAYSIA SABAH

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STUDY OF MELTING OF LOW TEMPERATURE METAL FOR FUSED FILAMENT FABRICATION (FFF) PROCESS

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THESIS SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF BACHELOR OF MECHANICAL ENGINEERING

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DECLARATION

I hereby declare that this project progress report entitled "Study of Melting of Low Temperature Metal for Fused Filament Fabrication (FFF) Process", submitted to Universiti Malaysia Sabah, is an original work under the supervision of Ir. Dr. Chua Bih Lii, and it is submitted as a partial fulfilment of the requirement for the degree of Bachelor of Mechanical Engineering, which has not been submitted to any other university for a degree. I also certify that the work described is entirely mine, except for quotations and summaries of sources which have been duly acknowledged.

18th July 2022

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CERTIFIED BY

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SUPERVISOR

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ABSTRACT

This project paper is about the adhesion of 2 dissimilar materials. The materials involved are metal and polymer. The concept is based on printing of solder track on Fused Filament Fabrication (FFF) printed model. The objective of this project is to construct an extruder suitable for the deposition of conductive materials on thermoplastic substrates fabricated by FFF process. Therefore, a prototype is constructed to carry out soldering to represent the metal printing process. The next objective is to investigate the optimum printing speed for the deposition and adhesion on the printed surface fabricated by FFF process. Thus, three printing speeds are calculated by adjusting the input pulse frequency of stepper motors and the optimum speed will be selected. Other than this, effect of surface conditions of thermoplastic substrates fabricated by FFF process on adhesion of conductive materials is investigated. Three printed substrates are surface treated with sandpaper, ironing and copper spray respectively to achieve this objective. From the results, the pattern of solder tracks for each printing speed is almost the same but the number of deposited solder beads and distance between successive beads are different. The slowest printing speed is chosen for the printing of solder tracks on surface treated substrate and the results show almost the same, indicating the insignificance of printing speed and surface condition on the adhesion of solder and PLA.

ABSTRAK

'KAJIAN PENCAIRAN LOGAM SUHU RENDAH UNTUK PROSES PEMBUATAN FILAMEN FUSED (FFF)'

Kertas projek ini adalah mengenai lekatan 2 bahan yang berbeza. Bahan yang terlibat ialah logam dan polimer. Konsep ini adalah berdasarkan cetakan trek pateri pada model cetakan Fused Filament Fabrication (FFF). Objektif projek ini adalah untuk membina penyemperit yang sesuai untuk pemendapan bahan konduktif pada substrat termoplastik yang direka oleh proses FFF. Oleh itu, prototaip direka bentuk dan dibina untuk menjalankan pematerian bagi mewakili proses percetakan logam. Objektif seterusnya adalah untuk menyiasat kelajuan cetakan optimum untuk pemendapan dan lekatan pada permukaan cetakan yang direka oleh proses FFF. Oleh itu, tiga kelajuan pencetakan dikira dengan melaraskan frekuensi nadi input motor stepper dan kelajuan optimum akan dipilih. Selain daripada ini, kesan keadaan permukaan substrat termoplastik yang direka oleh proses FFF ke atas lekatan bahan konduktif disiasat. Tiga substrat bercetak masing-masing diubahsuai dengan kertas pasir, seterika dan semburan tembaga untuk mencapai objektif ini. Daripada keputusan, corak trek pateri untuk setiap kelajuan cetakan adalah hampir sama. Kelajuan percetakan yang paling perlahan dipilih untuk mencetak trek pateri pada substrat yang diubahsuai permukaan dan hasilnya menunjukkan hampir sama, menunjukkan tidak pentingnya kelajuan percetakan dan keadaan permukaan pada lekatan pateri dan PLA.

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LIST OF ABBREVIATION

FFF – Fused Filament Fabrication

FDM – Fused Deposition Modelling

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CHAPTER 1
INTRODUCTION

1.1 Overview

Stepping into the era of Industrial Revolution 4.0, alongside with the increasing demand of end products in electronics, automotive, food, medical and construction industries, mass production with low cost and time consumption, while maintaining high product quality, has attracted a tremendous interest lately. To meet the manufacturing demand nowadays, digital fabrication technology, which is referred to as 3D printing or additive manufacturing (AM) has emerged and developed rapidly throughout the past few decades. The whirlwind developments of additive manufacturing has enabled 3D printing potential to transit from a rapid prototyping technique to a sophisticated technology capable of creating 3 dimensional objects through layer-wise assembling of components by using computer aided design (CAD) data (Cano et al., 2019).

Varieties of 3D printing are developed for different targeted applications and functions. According to ASTM Standard F2792, ASTM catalogued 3D printing technologies into seven groups, including the binding jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination and vat photopolymerization (Committee F42 on Additive Manufacturing Technologies, n.d.). Like other types of manufacturing processes, such as substrative and formative manufacturing, additive manufacturing requires materials that meet specific physical properties and compositions to build the functional parts. There is a wide range of material to be chosen, which includes ceramic, metallic, polymers and their combinations in the forms of hybrid, composites or functionally graded materials (FGMs) (Shahrubudin et al., 2019).

Material extrusion is one of the methods in addictive manufacturing. This layer-wise assembling 3D printing technology was first commercialized as Fused deposition modelling (FDM) by the company Stratasys for fabricating complex geometrical parts. According to ASTM F42 (Additive Manufacturing Technologies) terminology, this technology could also be termed as Fused Filament Fabrication (FFF) (Penumakala et al., 2020). It utilises the deposition of melted filaments through a nozzle to build a 3D structure layer by layer. FFF 3D printing is very common nowadays due to its affordability and availability. Complex shape 3D models can be created by using simple home FFF 3D printers with very low production costs, as compared to the other 3D printing technologies. Even though FFF 3D printing is commonly considered to be the technique for productions of plastic parts, attempts have been done for fabrications of other types of material like ceramics and metals with this technique (Mousapour et al., 2021).

According to Markforged, an additive manufacturing company, metal FFF 3D printing is accessible, affordable and user friendly, as compared to the other conventional metal 3D printing technologies in terms of mass adoption. Various industries, from automotive to aerospace, have adopted FFF 3D printing to produce a myriad of functional parts. This technique is based around metal injection molding (MIM) with the utilisation of 3 step processes, which include printing, debinding and sintering. During the printing process, metal powder bound in plastic is printed a layer at a time subsequently until a complete 3D model is formed, which is known as 'green' part at this stage. The part will be placed into a debinding station, where an organic solvent is used to dissolve most of the plastic binding material and the product is now known as 'brown' part. The part is then placed in a furnace to be heated with a material-specific profile so that the remaining binder is burnt away to solidify the metal powder into a finished part.

Even though FFF 3D printing has a broad range of applications in many industries and fields, the knowledge and experience in setting up the printing process parameters strongly determine the success rate of end products. The parameters include the deposition orientation, layer thickness, infill pattern, printing speed, extruder temperature and cooling, edge treatment, printing platform temperature, and enclosure ventilation. Therefore, the determination of significant parameters, which influence the dimensional accuracy, durability, and mechanical strength of functional parts, is done through the design of experiment method (Lee & Liu, 2019).

This project will focus on the study of melting of low temperature metal for FFF Process. Tin will be chosen as the subjected metal to be melted and deposited on a 3D printed PLA substrate to construct a printed circuit board (PCB). However, deposition of two dissimilar materials with different thermal properties results in the delamination and discontinuation of deposited bead. Therefore, an interest has risen to find out the suitable surface topology of PLA substrate, the appropriate printing speed and orientation, and the optimum temperature of extruder and tin deposition.

1.2 Problem Statement

To date, development of additive manufacturing has gained tremendous attentions due to its high potential for directly shaping of complex shape parts from computer aided design or 3D scanning system database (Ren et al., 2016). Therefore, 3D printing provides unlimited opportunities for fabricating customized functional parts without any requirement of dedicated tooling, resulting in reduced time span between design, testing and application (Jin et al., 2019). Due to the availability of this technology in fabricating customized and complex end products, myriad studies have been done on printing and embedding conductive electrical tracks on desired shape of 3D model to meet specific requirements to reduce number of parts, size and space of the whole mechatronics structure.

Nevertheless, the printing of electric circuits technology are still in infancy stages. The critical issue remains in the capability of fabricating electric circuits and wiring on the same layer or on different layers of 3D printed devices. The dimensions and geometry of the filament, as well as the deposition of conductive material and on the printed substrate, also affect the quality and accuracy of the printed parts (Bellacicca et al., 2018). The surface of a printed object is the most limiting factor for the printing of ink-based conductive track, which is not easily adoptable for embedded architecture (Tan & Low, 2018). The conductive filaments and the thermoplastic substrates are two dissimilar materials with different thermal properties, which lead to the delamination and discontinuation of deposited bead. Due to these factors, investigation on the surface topology of the printed PLA substrate and the temperature of extruded tin filaments, as well as the printing speed and orientation are required.

1.3 Research Objectives

There are three objectives needed to be achieved in this project as listed below:

1. To design and fabricate an autonomous soldering platform for the deposition of solder tracks on thermoplastic substrates fabricated by FFF process
2. To investigate the suitability of solder track deposition with different printing speeds on thermoplastic substrates fabricated by FFF process
3. To investigate the suitability of solder track deposition on thermoplastic substrates with different surface conditions fabricated by FFF process

1.4 Scope Of Works

To kick start this project, background study and research regarding additive manufacturing or 3D printing are done by reviewing past research articles and journals to provide a thorough and vital understanding on the project title and background, as well as specific keywords, such as additive manufacturing, Material Extrusion, Fused Filament Fabrications (FFF), 3D printed electronic devices and polymer/metal nanocomposites, to have a well illustration and planning on the design of experiment.

This project is based on experimental works. In other words, laboratory measurement are essential to complete this project. There are 3 main influencing aspects to be concerned in the design of experiment settings, which include soldering platform designation and fabrication, printing speed of conductive materials and printed substrate surface conditions. Analysing the printing speed of tin filaments on FFF fabricated PLA substrate with different surface topology is the main task to be done to come out with a suitable design of soldering platform, printing speed and substrate surface condition to demonstrate solder track deposition on the printed substrate.

1.5 Research Methodology

Methodology of this project has been split into four stages, which aim to conduct a study of melting of low temperature metal for FFF Process. The four stages include literature review, design of experiment and identification of process parameters, modelling and deposition, testing and manipulation of process parameters, and results analysis and documentation. A flowchart is constructed in Figure 1 to summarise the flow of methodology.

1.5.1 Literature Review

Past research papers and articles related to the study of melting of low temperature metal for FFF Process are reviewed and studied. This help to provide a well-rounded understanding on the conceptual knowledge behind each research, how the experiment should be designed and carried out, and what issue to be brought out in the problem statement. The idea and methodology obtained from the past researches are adopted as references in this project to provide assistants to design and develop a brand new set of experiment utilized to achieve the objectives of this project. Besides, past researches are referred to aid in the evaluation of experimental outcomes.

1.5.2 Design Of Experiment And Identification Of Process Parameters

The main concerns in the design of experiment and simulation settings include soldering platform designation and fabrication, conductive material printing speed and printed substrate surface condition. This study is carried out by developing a suitable design of soldering platform, printing speed of conductive material and substrate surface condition to ensure the deposition of conductive material on the printed substrates.

1.5.3 Modelling And Deposition

Suitable size of specimen is designed and modelled by using CAD software for printing and simulation purposes. This procedure is also done to ease in the measurement and amendment of specimen dimensions. The specimen CAD part file is converted to .STL file so that the virtual model is sliced into layers by using Cura Ultimaker software. The model is printed by using FFF 3D printer. Printing of conductive tin filaments on the printed model is done by soldering.

1.5.4 Manipulation Of Process Parameters

Manipulation of printing speed is done by using stepper motors with different input pulse frequency. PLA substrate specimens with different surface topology are obtained by sand paper polishing, ironing and copper spray coating.

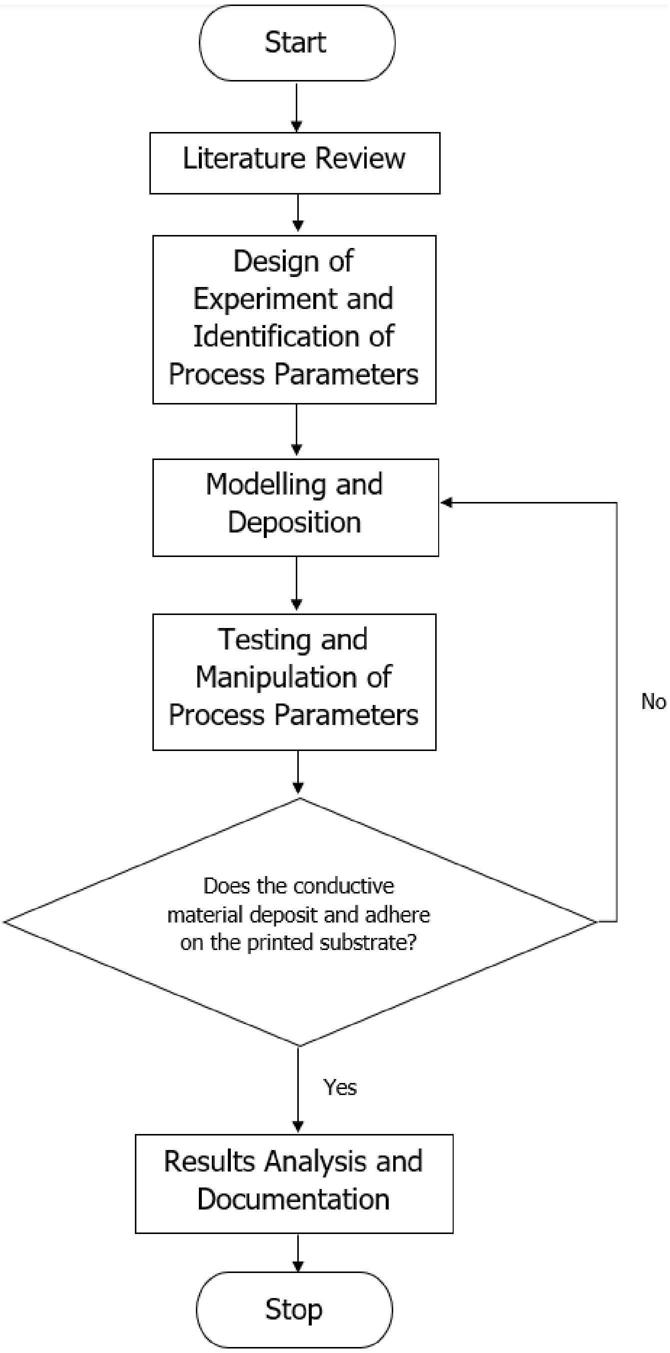

Figure 1: Flowchart of this project

1.6 Materials And Equipment

A list of equipment and material required in this project is presented as below:

i. Fused Filament Fabrication (FFF) 3D printer
ii. Soldering gun
iii. Multimeter
iv. 47 microFarad capacitor
v. Soldering wires
vi. Polylactic Acid (PLA) filaments
vii. Stepper motors
viii. A4988 motor drivers
ix. Jumper wires
x. 12V DC power jack
xi. Donut board
xii. Rubber
xiii. 3D printed Rack and Pinion Gears
xiv. 3D printed motor couplers
xv. Aluminium angled bar
xvi. Aluminium hollow bar
xvii. Aluminium flat bar

1.6.1 Costs And Expenses

Table 1 shows the expected expenses in this project.

Table 1: Expected expenses of this project

Items	Price (RM)
Polylactic Acid (PLA) filaments	70
Soldering wires	30
Electronics components	150
Aluminium bars	50
Others	25
Total	**325**

1.7 Research Expected Outcomes

This project is expected to produce research outcomes that conform with the objectives where all the objectives can be successfully achieved. The objectives are achieved by designing and fabricating the autonomous soldering platform so that the suitability of solder track deposition printed with different speed and on different surface conditions can be investigated.

1.8 Research Contributions

This paper provides a study on the deposition of conductive material on a thermoplastic having different thermal properties and the factors affecting the deposition. This paper can be documented for further references and studies on the related fields. The findings of this project will be able to promote and inculcate additive manufacturing knowledge among university students about the application of FFF 3D printing in smart electronics devices manufacturing industries.

1.9 Research Commercialization

As the main goal of this project is to investigate the suitability of solder track deposition on FFF printed substrate with different printing speeds and surface conditions, after an autonomous soldering platform is designed and fabricated. This project is done to provide a reference for the production of the designed soldering platform to provide a good deposition of conductive material on the thermoplastic substrate to fabricate smart electronic devices with electrical tracks embedded in complex shaped functional parts.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

In this project work, the study of melting of low temperature metal for FFF process will be carried out in the sense of embedding electronics circuits onto thermoplastic substrate surface. The thermoplastic utilised in this project work is polylactic acid (PLA), printed with Fused Filament Fabrication (FFF) or Fused Deposition Modelling (FDM) technique. The electronic circuits will be applied by using soldering, similar to ink jet fabrication technique. The soldering wires used is Sn60 – Pb40 type, that is available in the market. The issue arose that motivated the conduction of this project work is the challenges due to the infancy stage of printing electronic circuits technology that bring out the interest in the investigation of influences of printing parameters, such as nozzle temperature and printing speed, as well as the surface topology of printed substrate, such as the surface roughness, on the adhesion between the solder and PLA substrate. Hence, in this project work, an extruder which is suitable for the deposition of solder onto PLA substrate fabricated by FFF or FDM process will be proposed and designed. Also, the effect of surface conditions of PLA substrate on the adhesion of solder will be investigated. The printing speed of printed solder will be investigated too for its deposition and adhesion on the PLA substrate.

2.2 Three – Dimensional (3D) Printing

3D printing or Additive Manufacturing (AM) is a fabrication technique where the model is built by successive addition of material. The 3D model is fabricated through layer by layer fabrication technology tracking the design of virtual model drawn in Computer Aided Design (CAD) software. This technology has gained interests nowadays because it is able to increase the production rate while reducing manufacturing cost. It also eases students, researchers and hobbyists in the fabrication of prototypes for various purposes because of the customization ability and flexibility of 3D printing. This technology can be categorised into seven groups, comprising of the binding jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination and vat photopolymerization – based technique. Every technique has the targeted applications. The materials which can be used in 3D printing can be classified into metals, polymers, ceramics, composites with a wide range of fillers, smart materials and special materials, such as food and textile. Every material is used in various industries according to the printing technique used and end product specifications. 3D printing has tremendous applications in many industries. This includes aerospace, automotive, healthcare and medical industry, architecture, building and construction, fabric and fashion, electric and electronics, and food industries (Shahrubudin et al., 2019). Due to the wide range of applications provided by additive manufacturing technology, the interest in the current work arose to combine the printing of metal and polymer to fabricate embedded electronics circuits on thermoplastic substrate by Material Extrusion technique.

2.3 Fused Filament Fabrication (FFF) / Fused Deposition Modelling (FDM)

FDM is one of the techniques under AM. It is one of the most accessible 3D printing technique due to its high availability in the market and low utilization cost. It was developed by Stratasys in 1990s which then gains tremendous interests nowadays. It is popular among hobbyists, researchers and students due to its functionality to fabricate prototype by using thermoplastic filaments in – home or office – friendly environments as compared to other AM techniques that require specified equipment or well – controlled environment. FDM is user – friendly because the parts can be fabricated directly from virtual model created in CAD software, such as SolidWorks and Autodesk Inventors. FDM 3D printer requires tuning in terms of each individual process parameter to meet the suitability of each application so that a satisfied and quality printed model is fabricated. The process parameters can be classified into three types, which are, extruder related, process related and structural parameters. The selection of optimum set of parameters and appropriate process parameters is advantageous in dimensional accuracy, waste reduction, production time and production cost (Agarwal et al., 2022).

FDM is an AM technique where layer – by – layer deposition of molten polymeric filament is done on top of the others until the part is fully fabricated according to the virtual model design. The virtual model is designed in CAD software before the conversion of CAD file to .STL file and .STL file to G – code file are done. The part file is then virtually sliced in the slicer software like Cura and PrusaSlicer. The file is later input into FDM 3D printer for the part to be printed. The filament is first fed into the heated extruder to be melted. The nozzle has two degrees of freedom which displaces along x and y axes to shape each layer. On the other hand, the print bed displaces along z – axis every time a layer of deposition is finished by the nozzle. There are 3D printers equipped with nozzle that can move in x, y and z – direction to fabricate the model. There are also 3D printers equipped with multiple nozzles to extrude multiple filaments simultaneously. The nozzle and print bed are pre – heated to predetermined temperature to avoid the breaking of filament and clogging of nozzle, as well as the peel of 3D printed model from the print bed (Cano-Vicent et al., 2021).

According to the critical review done by Penumakala et. al. (2020), FDM has a wide range of applications, such as its application in the biomedical, tooling, aerospace and electronics industries. Among the stated applications, electronic application is the main interest in the current work. From the review, polymer composites with built in electrical feature and good feedstock filament processability are developed for the fabrication of dielectrics, conductors, sensors and energy storage parts by the researchers. Developments of carbon black and graphene – filled filaments are given attentions as the carbon black and graphene fillers are relatively cheaper than metal fillers with oxidizing tendency. The conductive filaments provide conductive path inside the polymers. This allow FDM to print electronics embedded devices or the whole electronic circuits. Studies have also been done on the use of ink deposition technique for printing electro chemical energy storage devices, where separate procedure for the in – situ curing and later polymerization are required. By using FDM, the devices are printed directly with the elimination of further curing steps. FDM provides a lot of future potentials that are beneficial in many manufacturing fields (Penumakala et al., 2020).