ELUCIDATING THE CORRELATIONS BETWEEN POST-PROCESSING PARAMETERS AND MECHANICAL PROPERTIES OF 3D PRINTED COPPER COMPOSITE

BY

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ABSTRACT

3D printing is a promising technology with the potential to revolutionize the additive manufacturing industry. Recently, the application of metal-based 3D Printing has been widely used especially in the aerospace, medical, and automotive industry. However, the cost of such machines is expensive and thus restricts access to this technology for small and medium enterprises. Thus, moving from expensive Selective Laser Melting (SLM) to Fused Deposition Modeling (FDM) Technology is a good alternative. Currently, the greatest challenges in advancing a low-cost FDM Metal 3D printing technology are post-processing, parameters affecting the post processes, accuracy, mechanical properties and microstructure of the finished parts. This project aims to investigate the post-processing techniques for 3D printed copper composites using an FDM 3D printer. To achieve the aim of this research, a hardened steel nozzle designed for metal composite filaments was used. Post-processing steps included debinding and sintering to convert the copper polymer composite into pure metal. The research employed the Design of Experiments (DOE) approach, specifically the Taguchi method, for optimization. An L8 orthogonal test array was constructed to determine the optimized parameters for debinding and sintering holding times. The findings revealed that the debinding process significantly affected shrinkage and hardness. The samples exhibited an average shrinkage of 30.59%, except for two samples that turned into small pieces due to improper debinding holding time. The debinding and sintering parameters played a crucial role in the successful conversion of the copper polymer composite into pure metal. These findings contribute to making metal 3D printing more affordable and accessible, opening up opportunities in different industries and supporting sustainable manufacturing practices. In future research, it is important to work on improving the way researchers finish the 3D printed metal parts. This includes finding better ways to remove binders and fuse the metal particles together during post-processing. Researchers should also look into simplifying the post-processing steps and finding ways to print larger parts.

خلاصة البحث

تعد الطباعة ثلاثية الأبعاد تقنية واعدة لها القدرة على إحداث ثورة في صناعة المواد المضافة. في الآونة الأخيرة ، تم استخدام تطبيق الطباعة ثلاثية الأبعاد القائمة على المعدن على نطاق واسع خاصة في صناعة الطيران والطب وصناعة السيارات. ومع ذلك ، فإن تكلفة هذه الآلات باهظة الثمن وبالتالي تقيد الوصول إلى هذه التكنولوجيا للمؤسسات الصغيرة والمتوسطة. وبالتالي ، فإن الانتقال من تقنية الذوبان الانتقائي ، يعد بديلًا جيدًا. حاليًا (FDM) الباهظة الثمن إلى تقنية نمذجة الترسيب المنصهر (SLM) بالليزر منخفضة التكلفة في مرحلة ما بعد FDM Metal 3D تتمثل أكبر التحديات في تطوير تقنية طباعة المعالجة ، والمعلمات التي تؤثر على عمليات ما بعد ، والدقة ، والخصائص الميكانيكية ، والبنية الدقيقة للأجزاء النهائية. يهدف هذا المشروع إلى التحقيق في تقنيات ما بعد المعالجة لمركبات النحاس المطبوعة ثلاثية الأبعاد. لتحقيق هدف هذا البحث ، تم استخدام فوهة FDM ثلاثية الأبعاد باستخدام طابعة فولاذية صلبة مصممة للخيوط المعدنية المركبة. تضمنت خطوات المعالجة اللاحقة التجليخ والتلبيد لتحويل وتحديدًا ، (DOE) مركب البوليمر النحاسي إلى معدن نقي. استخدم البحث نهج تصميم التجارب لتحديد المعلمات L8 من أجل التحسين. تم إنشاء مصفوفة اختبار متعامدة ، Taguchi طريقة المحسَّنة لتصفية وتلبيد أوقات الاحتفاظ. أوضحت النتائج أن عملية التنقية أثرت بشكل كبير على الانكماش والصلابة. أظهرت العينات انكماشًا متوسطًا بنسبة 40٪ ، باستثناء عينتين تحولتا إلى قطع صغيرة بسبب وقت احتجاز غير مناسب للكسر. لعبت معاملات التنقية والتلبيد دورًا مهمًا في التحويل الناجح لمركب بوليمر النحاس إلى معدن نقي. تساهم هذه النتائج في جعل الطباعة المعدنية ثلاثية الأبعاد ميسورة التكلفة ويمكن الوصول إليها ، مما يفتح الفرص في مختلف الصناعات ويدعم ممارسات التصنيع المستدامة. في البحث المستقبلي ، من المهم العمل على تحسين الطريقةالباحث ننهي بها الأجزاء المعدنية المطبوعة ثلاثية الأبعاد. يتضمن ذلك إيجاد طرق أفضل لإزالة الروابط ودمج جزيئات المعدن معًا أثناء المعالجة اللاحقة. يجب على الباحثين أيضًا النظر في تبسيط خطوات ما بعد المعالجة وإيجاد طرق لطباعة أجزاء أكبر

APPROVAL PAGE

I certify that I have supervised and read this study and that in my opinion; it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a thesis for the degree of Master of Science in Manufacturing Engineering.

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I hereby declare that this thesis is the result of my own investigations, except where otherwise stated. I also declare that it has not been previously or concurrently submitted as a whole for any other degrees at IIUM or other institutions.

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LIST OF ABBREVIATIONS

3D	Three Dimension
SLM	Selective Laser Melting
FDM	Fused Deposition Modeling
AM	Additive Manufacturing
CAD	Computer Aided Design
SLS	Selective Laser Sintering
LPBF	Laser Powder Bed Fusion
EBM	Electron Beam Melting
PLA	Polylactic Acid
ABS	Acrylonitrile Butadiene Styrene
EDX	Energy Dispersive X-Ray Spectroscopy
PBF	Powder Bed Fusion
CO2	Carbon Dioxide
TPU	Thermoplastic Polyurethane
PA6	Polyamide six
PA12	Polyamide twelve
DMLS	Direct Metal Laser Sintering
EB PBF	Electron Beam Powder Bed Fusion
ADAM	Atomic Diffusion Additive Manufacturing
FFF	Fused Filament Fabrication
Al	Aluminum
Cu	Copper
Fe	Iron
O	Oxygen
Ca	Calcium

Mg	Magnesium
MIG	Metal Inert Gas
GTAW	Gas Tungsten Arc Welding
NDT	Non-Destructive Testing
SEM	Scanning Electron Microscopy
DOE	Design of Experiments
RF	Radio Frequency
SED	Scanning Electron Microscopy Electron Detector
WD	Working Distance
HV	Vickers Hardness

CHAPTER ONE

INTRODUCTION

1.1 OVERVIEW

This introductory chapter lays down a foundation and discusses the background of this thesis, describes broadly the problem statement that this thesis will deal and from that identifies objectives to be solved detailed methodology is discussed at the end of this chapter.

1.2 BACKGROUND OF THE STUDY

3D printing or additive manufacturing (AM) is a group of technologies that are used to build prototypes, physical models and finished parts from three-dimensional (3D) computer-aided design (CAD) data. Studies showed that technology has developed rapidly since it is reshaping the manufacturing industry with foreseeable benefits including complex designs, greater structural efficiency, reduction in material consumption and wastage, enhanced customization, and improved accuracy and safety. There has been an increase in demand for metal prototypes and tools. The introduction of non-polymeric material, including metal, has been widely used in 3D printing applications. Subsequently, powder bed fusion is a specific 3D printing technique which uses high power-density laser to melt and fuse metallic powders such as Selective Laser Sintering (SLS), Laser Powder Bed Fusion (LPBF), Electron Beam Melting (EBM), and among these technologies SLS or SLM technology has the highest demand in the market. And a commercial example of Selective Laser Melting is a DMG Mori Lasertec 12 SLM 3D printer, a German-made 3D Printer with a cost of 2.3 million Ringgit. Therefore, such machines are too expensive and thus restrict access to this technology for small and medium enterprises. Another 3D printing technology that can print metal is a material extrusion technology which is subdivided into Fused Deposition Modelling (FDM), 3D Bioprinting, and Construction 3D Printing, and among these technologies Fused Deposition Modelling (FDM) technology has the highest demand in the market as it is the most affordable technology in the market as it ranges from RM500 to RM30000 (Ramazani & Kami, 2022) .

The purpose of this research is to investigate to print metal in a low-cost Fused Deposition Modelling 3D printer with effective post-processing parameters by utilizing the novel ideas and resources of previous research. Currently, the primary metal 3D printing heat sources are lasers, electron beams and electric arcs. The research and applications of lasers in metal 3D printing are extensive; Laser heating produces high-precision parts with good internal structures and great mechanical properties. However, lasers and metal powders are expensive (Huang et al., 2023) but coming to Fused Deposition Modelling based on a previous study, the welding process was used in this method to build 3D parts for the first time where containers and useful shapes were produced. Similarly, a scholar had successfully developed a 3D structure using a rapid prototyping process with a combination of micro tungsten inert gas welding and a layered manufacturing method in an FDM 3D printer. The results showed that a 3D structure without mould for micro component metals with high strength and oxidization resistance can successfully be built. The research was carried out by Kumar Singh & Chauhan, (2016) where they enhanced a technique of printing metal in an FDM 3D printer by using an Induction furnace and ceramic nozzle with a Tungsten tip. But in all the above FDM 3D printing methods, the metal parts were printed with the lowest resolutions and couldn't make any use of such parts in printing prototypes or any industrial component due to lack of accuracy. Thus, implementing an alternative method to print Metal using a Fused Deposition Modelling 3D Printer. This research is anchored on the assumptions that adding a hardened steel nozzle to the Extruder using to melt the metal filament which is more affordable and simpler than using the Laser-Metal Wire Deposition method or Tungsten inert gas method. However, the Filament used to print is a polymer-metal which consists of pure Metal powder whereas the polymer material is made of Polylactic Acid and Binding agents such as Polyethylene Wax. This helps the filament to print as normally as PLA or ABS. But the disadvantage of polymer-metal filament is that it will break more easily due to its high metal content hence avoiding pull and friction requires the filament to come off the spool straight into the feeder which normalizes the printing process. Further, it requires post-processing by removing the polymer or binding agent from the printed part by the debinding method and then heating the remaining 3D printed pure metal part by Sintering method to fuse the atomic particles and to attain higher tensile strength. As a result, we can utilize such precise and higher-resolution metal parts to print especially Orthopaedic implants on a simple desktop FDM 3D printer. And since additive manufacturing is envisioned as the future of manufacturing, our abundance of locally high-quality materials must be capitalized upon effectively. To be self-sustainable and technologically forward in the foreseeable future, researchers must invest in this technology. The significance of this research is to provide knowledge and establish curiosity and fascination towards the Aerospace industry among academic researchers in Malaysia contributing to the development of economic growth Malaysia needs "Big innovation purpose" to stay ahead, says its government agency creating jobs, and facilitating international trade and tourism in the country. Aerospace engineers are the key people for making the next step for humans to travel faster around the world and explore the technological capabilities of flying vehicles.

1.3 PROBLEM STATEMENT

Metal 3D printing is a promising technology for producing complex and high-performance parts for various applications, especially in the aerospace, medical prosthetics and Automobile industry. However, metal 3D printing using laser-based methods is very expensive and requires specialized equipment and materials. Therefore, researchers have explored alternative methods of metal 3D printing using fused deposition modelling (FDM) technology, which is more accessible and affordable. FDM metal 3D printing uses a metal-polymer filament that consists of 90% metal powder and 10% polymer binder. The printed part contains 90% of metal powder, which can be converted into pure metal by post-processing steps of debinding and sintering.

However, FDM metal 3D printing also faces some challenges, mainly related to the post-processing parameters. Debinding and sintering are critical steps for achieving the desired mechanical properties of the printed metal part, such as strength, ductility and density. However, if the post-processing parameters are not optimized, the printed metal part may suffer from defects such as cracks, unsintered regions, brittleness, complete melting of the part, and the inability to achieve the desired shape. Moreover, the microstructure of the printed metal part may exhibit the presence of undesirable pores, which can affect its performance and reliability.

Therefore, this study aims to investigate the rheological characteristics of copper-based metal composites and examine how their processing and post-processing parameters affect their quality and performance. Copper-based metal composites are chosen because they have high electrical and thermal conductivity, corrosion resistance and mechanical strength, which make them suitable for various applications (Ambrus et al., 2021). The study will use FDM technology to print copper-based metal composites with different compositions and geometries. The study will also analyse the effects of different debinding and sintering parameters on the mechanical properties, microstructure and density of the printed metal parts. The study will provide insights into the optimal processing and post-processing conditions for FDM metal 3D printing and contribute to the advancement of this technology.

1.4 RESEARCH OBJECTIVE

The research aims to investigate the fabrication of metal using FDM 3D Printer with effective post-processing techniques. The objective is to conduct a quantitative study of literature and industry practices. Specifically, the study has the following objectives:

- To fabricate metal 3D printed samples by using the fused deposition modelling (FDM) technique.
- To identify the optimized holding time and temperature using the Taguchi method for post-processing of FDM printed metal parts in the debinding and sintering process with different layer thicknesses.
- To investigate the effects of post-processing parameters on the mechanical properties, dimensions, chemical composition and microstructure, of sintered copper composite parts.

1.5 SIGNIFICANCE OF RESEARCH

The research on Fused Deposition Modelling (FDM) metal 3D printing and its post-processing techniques is significant for several reasons. It aims to make metal 3D printing more accessible and affordable by overcoming the cost limitations of traditional methods. This opens up opportunities for small and medium enterprises and individuals to utilize this technology. Additionally, the research advances industrial applications, particularly in aerospace, medical prosthetics, and automotive industries, by improving the mechanical properties of FDM-printed metal parts. It optimizes post-processing parameters to enhance the quality and performance of the printed components. Furthermore, the research contributes to knowledge and stimulates further advancements in the field of metal additive manufacturing. It also has economic implications, fostering growth, innovation, and job creation, particularly in countries like Malaysia. Overall, this research drives progress in metal 3D printing, making it more accessible, efficient, and impactful across various industries.

1.6 SCOPE OF THE RESEARCH

The scope of this research study is to investigate the impact of post-processing techniques on the mechanical properties and dimensional accuracy of metal 3D printed samples using the Fused Deposition Modeling (FDM) method. The specific objectives include assessing the effects of sintering temperature on hardness and measuring the shrinkage percentages of printed samples after the sintering process. Additionally, the study aims to determine the presence of pores, diffusion of metal particles, and the chemical composition, particularly the percentage of copper, in the samples. The research will be conducted using a sample size of 8 printed samples, each measuring 25x25x5 mm. The study duration is set at 3 months, and the methodology encompasses Design of Experiments using the Taguchi method, sample preparation, printing process control using a standard FDM printer with predefined parameters, post-processing steps such as debinding and sintering at different temperatures ranging from 800°C to 1200°C with a constant heating rate and holding time, mechanical analysis using micrometers and Vickers hardness testing, and microstructure and chemical analysis using scanning electron microscopy and energy-dispersive X-ray spectroscopy (EDX). The scope acknowledges the limitations of the sample size and duration, ensuring practicality and feasibility while providing valuable insights into the specified research parameters. The scope also excludes other post-processing techniques such as polishing or coating, other metal materials such as steel or aluminum, other printing methods such as selective laser melting or direct metal laser sintering, and other mechanical properties such as tensile strength or fatigue resistance.

1.7 THESIS OUTLINE

This thesis is organized into five chapters:

Chapter 1 – Chapter One introduces the background, problem statement, research objectives, significance, scope and organization of the study.

Chapter 2 – Chapter Two reviews the relevant literature on different types of 3D printer technologies, metal 3D printing, FDM metal 3D printing, filament used in metal FDM 3D printers, process parameters for 3D printing metal in FDM 3D printers, post-processing techniques for FDM metal parts, mechanical characterization and performance evaluation in FDM metal printing, and FDM metal 3D printing applications in aerospace, medical and automobile field.

Chapter 3 – Chapter Three describes the research methodology, including the research design and approach, materials and equipment, sample preparation, printing process, post-processing, mechanical analysis, microstructure and chemical analysis, and data collection and analysis methods.

Chapter 4 – Chapter Four presents the results and discussion of the experimental work, including the experimental setup, process parameter optimization, post-processing, mechanical properties analysis, microstructural characterization.

Chapter 5 – Chapter Five concludes the thesis with a summary of key findings and recommendations for future research

CHAPTER TWO

LITERATURE REVIEW

2.1 INTRODUCTION

As the global interest in the automation industry rises, researchers are rapidly investigating different ways to improve the Additive manufacturing technology. Various industries have incorporated 3D printers to simultaneously improve efficiency and customizability. So, an alternative method is found recently by some companies like Mark forge, virtual foundry, etc. and researchers have started further studies on this method where a metal polymer composite filament is used to fabricate using a low-cost desktop Fused Deposition Modelling 3D printer (Ramazani & Kami, 2022). This research investigates how copper-polymer composite can be fabricated using low cost FDM 3D printing technology with optimized post processing parameters.

2.2 IMPORTANCE OF METAL

Metals on the other hand are important for various reasons such as their durability, conductivity, and malleability, making them ideal for use in construction, electrical wiring, and manufacturing. They also have high melting and boiling points, which makes them useful for high-temperature applications. Metals are usually very strong, most durable and highly resistant to everyday wear and tear. As such, they have been used since ancient times for a lot of things. And even today with advances in technology and a lot of other things the uses of metals have broadened greatly. Metals even play a key role in the economy.

Metals are found in every substance or thing related to the modern world; from cars to the crockery, from Jewelry to the buildings, hence, everything that exists in this modern world has to an extent metal utilization. They are used extensively in manufacturing machines for industries, agriculture or farming and automobiles which include road vehicles, railways, Aero planes, rockets etc. Here, the commonly used metals are iron, Aluminum and steel. Besides these, most of the utensils that are used in the kitchen are made from metals like steel, Aluminum, and Copper (Ngo et al., 2018).

2.3 TYPES OF METAL 3D PRINTING

2.3.1 Powder Bed Fusion

Powder bed fusion (PBF) is a 3D printing process where a thermal energy source selectively melts powder particles (plastic, metal, or ceramic) inside a build area to create a solid object layer by layer. Powder bed fusion 3D printers spread a thin layer of powdered material over the print bed, typically with a type of blade, roller, or wiper. Energy, typically from a laser, fuses specific points on the powder layer, then another powder layer is deposited and fused to the previous layer. The process repeats until the entire object is fabricated. The final item is encased and supported in unfused powder. Although the process varies depending on whether the material is plastic or metal, PBF can create parts with high mechanical properties including strength, wear resistance, and durability for end-use applications in consumer products, machinery, and tooling. Although the 3D printers in this segment are becoming more affordable (starting prices hover around $25000 to $1million), it is considered professional or industrial technology. The materials used in this technology are Plastic powders, metal powders and ceramic powders. And the common applications this technology offers are functional parts, complex or low-run part production (Fu & Körner, 2022)

2.3.1.1 Selective Laser Sintering (SLS)

Figure 2.1 shows Selective laser sintering (SLS) technology that can create objects out of plastic powder by using a laser. First, a bin of polymer powder is heated to a temperature just below the polymer’s melting point. Next, a recoating blade or wiper deposits a very thin layer of the powdered material – typically 0.1 mm thick – onto a build platform. A laser (CO_2 or fiber) then begins to scan the surface according to the pattern laid out in the digital model.