Faculty of Manufacturing Engineering

INTEGRATION OF ULTRASONIC AND VACUUM SYSTEM IN ADDITIVE MANUFACTURING TO REDUCE STAIRCASE EFFECT OF PRINTED PARTS

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Master of Science in Manufacturing Engineering

2020

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A thesis submitted
in the fulfilment of the requirements for the degree of Master of Science
in Manufacturing Engineering

Faculty of Manufacturing Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2020

DECLARATION

I declare that this thesis entitled “Integration of Ultrasonic and Vacuum System in Additive Manufacturing to Reduce Staircase Effect of Printed Parts” is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature : ……………………………….

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Date : ……………………………….

APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Master of Science in Manufacturing Engineering.

Signature	:	……………………………….
Supervisor Name	:	Associate Professor Dr. Shajahan bin Maidin
Date	:	……………………………….

DEDICATION

In the name of Allah, the Most Gracious and Most Merciful

Dedicated to my ummi and walid

Beloved zaujah and daughter

Cherished siblings

Honourable supervisors and lecturers

Faithful friends

ABSTRACT

Additive Manufacturing (AM) has come a long way since the days of rapid prototyping began with the capability to produce a complex solid part rapidly. AM has begun to be acknowledged and accepted in numerous industries such as aerospace, automotive, medical, and even art. Fused deposition modeling (FDM), one of the AM technologies, is a popular and most used technology based on polymer extrusion method. FDM generally works by depositing a molten thin polymer filament from the nozzle onto the build platform repeatedly layer by layer up to create a solid part. Despite having the advantages to produce part without any complexity restrictions, the known poor surface roughness for aesthetic and functional part produced is the limitation. Literature has found out that one of the main reasons related to thermal aspects, resulting from layer by layer manufacturing nature called as the "stair-stepping" effect. The layer by layer bonding occurred too fast and was not fully solidified together, causing semi-molten layered thermoplastic surface often uneven which cause rough and poor surface finish. It was found that ultrasonic and vacuum technology could improve the layer bonding by ultrasonic energy absorption and reducing the convective heat transfer. The ultrasonic energy absorption by the semi-molten thermoplastic molecule will cause it to vibrate energetically and cause a rapid rise in temperature and delayed the rapid cooling rate. In a vacuum environment, the reduced amount of air molecules hindered the heat energy to be released from the deposited filament. The surface roughness test conducted from pilot test confirmed that the different value of ultrasonic frequency and level of vacuum pressure does affect the surface roughness of the printed specimens. Then, a total 18 experiments runs generated by using DOE with 54 printed specimens were conducted with two parameters namely ultrasonic frequency and vacuum pressure. The surface roughness quality evaluated through the portable surface roughness tester and optical microscope. Result has found out that the highest percentage improvement (32.77 %) 12.92µm produce by 0kHz/-21inHg. It was found out that under optical microscope, the specimens produced under ultrasonic vibration and vacuum pressure had a better surface roughness compared to normal atmospheric ones. Lastly, the RSM and ANOVA method had validated the significance of the set parameters and the optimised process parameter was 49.56 kHz/-21 inHG for optimal solution of 9.46µm. The ultrasonic and vacuum system integrated FDM was proven to be feasible and this study had increased the understanding of ultrasonic and vacuum technology and FDM to improve the surface roughness of the printed part. Further improvements of ultrasonic and vacuum integrated FDM will allow the creation of improved surface finish quality of complex parts in a wide range of applications.

INTEGRASI SISTEM ULTRASONIK DAN VAKUM DALAM PEMBUATAN TAMBAHAN UNTUK MENGURANGKAN KESAN TANGGA PADA OBJEK DICETAK

ABSTRAK

Pembuatan secara tambahan "additive manufacturing" (AM) telah berkembang dari proses pembuatan tambahan bermula dengan keupayaan untuk menghasilkan bahagian pepejal yang kompleks dengan cepat. AM telah mula diakui dan diterima di industri seperti aeroangkasa, automotif, perubatan, dan juga seni. Pemodelan secara pemendapan "fused deposition modeling" (FDM), salah satu teknologi AM, adalah teknologi yang popular dan paling kerap diguna pakai berdasarkan kaedah penyemperitan polimer. FDM berfungsi dengan mendepositkan filamen polimer nipis cair dari muncung ke platform berulang kali lapisan demi lapisan sehingga menghasilkan objek pepejal. Walaupun mempunyai kelebihan untuk menghasilkan objek dengan mudah, kekasaran permukaan yang kurang memuaskan diketahui umum adalah kelemahannya bagi nilai estetika dan fungsi. Kajian literasi telah menemui salah satu sebab utama yang adalah berkaitan aspek termal, hasil daripada sifat pembuatan lapisan demi lapisan sendiri yang dipanggil sebagai "kesan tangga". Ikatan lapisan ini berlaku terlalu cepat dan tidak sepenuhnya terikat bersama-sama, menyebabkan permukaan termoplastik antara lapisan sering tidak sekata yang menyebabkan permukaan kasar dan tidak berkualti. Diketahui teknologi ultrasonik dan vakum boleh meningkatkan ikatan lapisan dengan penyerapan tenaga ultrasonik dan mengurangkan pemindahan haba secara konveksi. Penyerapan tenaga ultrasonik oleh molekul termoplastik separuh cair akan menyebabkan ia bergetar dan menyebabkan kenaikan suhu yang cepat dan melambatkan proses penyejukan cepat berlaku. Dalam persekitaran vakum pula, jumlah molekul udara yang dikurangkan menghalang tenaga haba untuk bergerak dari kawasan bercetak. Ujian kekasaran permukaan dari ujian rintis sahkan perbezaan nilai frekuensi ultrasonik dan tekanan vakum memberi kesan kepada kekasaran permukaan spesimen objek. Kemudian, sejumlah 18 eksperimen berjalan dijana menggunakan DOE dengan 54 spesimen bercetak telah dijalankan bersama dua parameter iaitu frekuensi ultrasonik dan tekanan vakum. Kualiti kekasaran permukaan yang dinilai melalui penguji kekasaran permukaan mudah alih dan mikroskop optik. Keputusan menunjukkan peningkatan peratusan tertinggi (32.77%) 12.92µm dihasilkan oleh 0kHz / -21inHg. Difahamkan di bawah mikroskop optik, spesimen yang dihasilkan di bawah getaran ultrasonik dan tekanan vakum mempunyai kekasaran permukaan yang lebih baik berbanding dengan normal. Akhir, kaedah RSM dan ANOVA mengesahkan kepentingan parameter set dan parameter yang dioptimumkan ialah 49.56 kHz / -21 inHG untuk penyelesaian optimum 9.46µm. Sistem ultrasonik dan vakum yang bersepadu FDM terbukti boleh dilaksanakan dan kajian ini telah meningkatkan pemahaman teknologi ultrasonik dan vakum dan FDM untuk mengurangkan kekasaran permukaan objek. Penambahbaikan lanjut FDM integrasi ultrasonik dan vakum akan membolehkan penghasilan kualiti permukaan yang lebih baik bagi bahagian kompleks dalam pelbagai aplikasi.

ACKNOWLEDGEMENTS

First and foremost, thanks to Allah S.W.T, the Almighty God for His mercy and grace in moving and enabling me to complete this thesis. I would like to take this opportunity to express my deepest gratitude to my supervisor, Associate Professor Dr. Shajahan Bin Maidin, from the Faculty of Manufacturing Engineering, Universiti Teknikal Malaysia Melaka (UTeM), who passionately guided and supported me towards the completion of this thesis. His unwavering enthusiasm kept me constantly involved with my research. I am equally thankful to my co-supervisor, Dr. Suriati Binti Akmal from the Faculty of Manufacturing Engineering, for her mentoring and encouragement. Special thanks to Minister of Higher Education (MOHE) and UTeM for providing the funding of Fundamental Research Grant Scheme (FRGS) and a high-quality learning platform. Above ground, I am thankful for my wife, Nurul Ain Binti Kamarudin and daughter, Aisy Nufa Inara Binti Ahmad Syafiq, families, relatives and friends with their moral support. Lastly, thank you to all who kept me going directly or indirectly and this completion of thesis would not have been possible without them all.

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LIST OF ABBREVIATIONS

3D	-	3 Dimensional
ABS	-	Acrylonitrile Butadiene Styrene
AM	-	Additive Manufacturing
ANOVA	-	Analysis of Variance
ASTM	-	American Society for Testing and Materials
CAD	-	Computer Aided Design
CAE	-	Computer Aided Engineering
CAM	-	Computer Aided Manufacturing
CNC	-	Computer Numerical Control
DED	-	Direct Energy Deposition
DOE	-	Design of Experiment
DOF	-	Degree of Freedom
EBM	-	Electron Beam Melting
FDM	-	Fused Deposition Modeling
GMDH	-	Group Method of Data Handling
inHg	-	Inch Mercury
Kn	-	Knudsen Number
LAN	-	Local Area Network
LOM	-	Laminated Sheet Manufacturing
MMR	-	Material Removal Rate

Nu	-	Nusselt Number
PEEK	-	Polyether-Ether-Ketone
PET	-	Polyethylene Terephthalate
PLA	-	PolyLactic Acid
PMMA	-	Poly(Methyl Methacrylate)
Ra	-	Rayleigh Number
SLA	-	Stereolithography
SLM	-	Selective Laser Melting
SLS	-	Selective Laser Sintering
STL	-	Stereolithography
TEM	-	Transmission Electron Microscopy
UAM	-	Ultrasonic Additive Manufacturing

LIST OF PUBLICATIONS

Maidin, S., Mohamed, A.S., Akmal, S., Mohamed, S.B., and Wong, J.H.U., 2018. Feasibility Study of Vacuum Technology Integrated Fused Deposition Modelling to Reduce Staircase Effect. *Journal of Fundamental and Applied Sciences,* 10(1S), pp.633-645.

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CHAPTER 1

INTRODUCTION

1.1 Background

A three-dimensional (3-D) model provides a lot better and easier way to visualize the shape and size of an object or model rather than two-dimensional (2-D) rendering or image. In the past years, designers and engineers would have wanted a 3D model of a planned model which can be overall evaluated. Traditional ways of making it, by ordering a custom made from metal or wood, which usually need a skilled model maker and very costly in term time and money. By any chance, if the result of evaluation, design change recommended, it will lead to more time and money had to be spent. By the nick of time, with the introduction of computer-aided-additive manufacturing 20 years ago, bring a new spark in the industry. Making a model or prototype was time consuming. As a result, the cost of each model was drastically minimized. Since that time the technology has grown and has achieved global status.

Nowadays, additive manufacturing (AM) is one of the common technique employed for the fabrication and it is currently being promoted as the new trend industrial revolution. The technologies of AM possesses capability of producing complex geometries with slight post-processing and low material waste while broadly applicable to variety of materials including metals and polymers (Canada, 2015; Ning et. al., 2015). Thus, with huge design of freedom offered by AM technologies, it would provide alternative to allow engineers and designers to produce and design any product economically for prototyping and manufacturing purpose in a small volume (Wong and Hernandez, 2012; Bikas et. al., 2016). AM technology effortlessly generates and builds 3D prototypes from concepts and ease manufacturing as well as assembly jobs. This kind of flexibility makes AM technologies upsurge in manufacturing technology (Croccolo et. al., 2013).

Fused Deposition Modeling (FDM) is one of the most used and well known in AM technologies (Maidin et. al., 2015), capable of printing complex geometry for polymer parts. The main practice for FDM technology is to adopt 3D Computer-Aided-Data (CAD) data to create polymer objects. The CAD model is constructed and converted to STL file with slices. Subsequently, with an appropriate setup, such layer height, infill percentage and others, tool paths will be generated and transferred to the FDM machine for fabrication. In FDM machine, a coil of thermoplastic filament supplied to the extrusion nozzle, heated to appropriate temperature, extruded and deposited a thread of semi-molten thermoplastic polymer to form a required geometry (Jain and Kuthe, 2013; Nidagundi et. al., 2015). A functional application from FDM printed parts required fine and smooth surface finish quality, accurate dimensional accuracy and good mechanical strength of parts which is crucial to optimize factor to achieve desired quality build of parts fabricated (Kumar et. al., 2012; Nidagundi et. al., 2015).

Literature review has found there is a gap in knowledge where ultrasonic application only applied in subtractive manufacturing (machining) and little work has been done to investigate the application of ultrasonic for additive manufacturing as well as the vacuum system technology. Generally, to aid the investigation, this research used a common piezoelectric transducer in a horizontal wave mode was attached in contact onto the nozzle area of a FDM UP Plus 2. A function generator with a maximum power of 20V comes with alterable frequency used to supply electrical power to generate some desirable frequencies. In addition, to set up the vacuum system, an acrylic of 12mm thickness and inner dimension of 350x390x400mm rectangular shape size was securely closed, remain