Faculty of Mechanical Technology and Engineering

INFLUENCE OF CONTROLLED OXYGEN LEVELS ON TENSILE STRENGTH, SURFACE ROUGHNESS, AND WARPING IN FDM PRINTS

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A thesis submitted in fulfillment of the requirements for the Master of Science in Mechanical Engineering

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DECLARATION

I declare that this project thesis entitled "Influence of Controlled Oxygen Levels on Tensile Strength, Surface Roughness, and Warping in FDM Prints" is the result of my work except as cited in the references.

Signature :

Name : Muhamad Arifuddin bin Che Mat

Date : 20/5/2024

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 Mechanical Engineering.

Signature :

Name of Supervisor: Faiz Redza bin Ramli

Date : 27/6/2024

DEDICATION

I would like to dedicate my appreciation to my supervisor Dr.Faiz Redza bin Ramli, and my co-supervisor, Dr. Mohd Nizam bin Sudin, who has given me a lot of guidance in this research. My best friends, Mohamad Nordin bin Mohamad Norani and Nor Ana Binti Rosli, have always guided me and willingly shared their knowledge and experience. Finally, I would like to thank my parents, Che Mat bin Jusoh and Kartini Binti Mohammad, for their unwavering financial support.

ABSTRACT

Fused deposition modeling (FDM) is one of the most widely utilized additive manufacturing techniques. However, the main limitations of FDM are poor surface roughness, low tensile strength, and significant warping deformation, which affect manufacturability and hinder the precision and quality of printed components. This study presents a new technique that improves the quality of FDM printed specimens by incorporating inert gases, such as nitrogen or argon, into the 3D printing chamber. The chamber was designed with openings for the inert gas to flow in at 12 $m^3 h^{-1}$ and +5 bar pressure and an outlet for gas to be released, monitored by an oxygen detector to control degradation factors. The effect of the inert gas on 3D printed specimens by the objectives, i.e. to investigate the effect of inert gas on the tensile strength of FDM-printed samples under varying printing process parameters, to analyze the surface roughness and bonding formation of the printed samples and to identify warping deformation in the printed samples. The research reveals several key findings. First, Cu/PLA exhibited the highest tensile strength compared to PLA and ABS at a layer thickness of 0.3mm, indicating that increased layer thickness correlates with increased tensile strength. Additionally, Cu/PLA showed superior SEM results, featuring structures with minimal air gaps compared to PLA and ABS. Second, both $Ar\text{-}O_2$(0%) and $N_2\text{-}O_2$(0%) conditions significantly improved tensile strength compared to printing without inert gas, with $Ar\text{-}O_2$(0%) demonstrating the most notable effect by producing uniform interlayer bonding, as evidenced by SEM images. Third, in terms of surface roughness, Cu/PLA outperformed PLA and ABS, with Face 4 achieving the best results under the $N_2\text{-}O_2$(0%) condition. The improvement in surface roughness was up to 24.71% between Face 4 and Face 1 at a 0.2mm layer thickness. SEM images revealed that areas with higher surface roughness correlated with more pronounced surface irregularities, such as grain boundaries and pores. Finally, both $N_2\text{-}O_2$(0%) and $Ar\text{-}O_2$(0%) inert conditions enhanced surface roughness compared to non-inert conditions. SEM analysis indicated that $Ar\text{-}O_2$(0%) produced minimal air gaps, facilitating strong connections between adjacent filaments and reducing void areas. In conclusion, the study affirms that the application of an inert gas environment during 3D printing is a highly effective strategy for improving the mechanical properties and surface quality of printed specimens. The findings offer valuable guidance for future research and development in the field of additive manufacturing, promoting the adoption of advanced techniques to achieve superior material performance and quality in 3D printed products.

PENGARUH KAWALAN TAHAP OKSIGEN TERHADAP KEKUATAN TEGANGAN, KEKASARAN PERMUKAAN, DAN LEDINGAN DALAM CETAKAN FDM

ABSTRAK

Pemodelan pemendapan terlakur (FDM) adalah salah satu teknik pembuatan tambahan yang paling banyak digunakan. Walau bagaimanapun, had utama kepada FDM adalah kekasaran permukaan yang tidak baik, kekuatan tegangan yang rendah, dan ubah bentuk ledingan yang ketara adalah mempengaruhi kemampuan pembuatan dan menghalang ketepatan serta kualiti komponen yang dicetak. Kajian ini memperkenalkan teknik baru yang meningkatkan kualiti spesimen cetakan FDM dengan mengalirkan gas lengai seperti nitrogen atau argon, ke dalam ruang pencetakan 3D. Ruang tersebut direka dengan bukaan untuk gas lengai mengalir masuk pada kadar 12 m^3 h^{-1} dan tekanan +5 bar, serta bukaan untuk pelepasan gas, yang dipantau oleh pengesan oksigen untuk mengawal faktor degradasi. Kesan gas lengai pada spesimen cetakan 3D dinilai berdasarkan objektif berikut iaitu untuk melihatt kesan gas lengai terhadap kekuatan tegangan sampel cetakan FDM di bawah pelbagai parameter proses pencetakan, menganalisis kekasaran permukaan dan pembentukan ikatan sampel cetakan, dan mengenal pasti ubah bentuk ledingan dalam sampel cetakan. Penyelidikan ini menunjukkan beberapa penemuan utama. Pertama, Cu/PLA menunjukkan kekuatan tegangan tertinggi berbanding PLA dan ABS pada ketebalan lapisan 0.3mm, yang menunjukkan bahawa peningkatan ketebalan lapisan berkorelasi dengan peningkatan kekuatan tegangan. Selain itu, Cu/PLA menunjukkan hasil SEM yang baik, dengan struktur yang mempunyai jurang udara yang minimum berbanding dengan bahan PLA dan ABS. Kedua, keadaan Ar-O_2(0%) dan N_2-O_2(0%) secara signifikan meningkatkan kekuatan tegangan berbanding pencetakan tanpa gas lengai, dengan Ar-O_2(0%) menunjukkan kesan yang paling ketara dengan menghasilkan ikatan antara lapisan yang seragam, seperti yang ditunjukkan oleh imej SEM. Ketiga, dari segi kekasaran permukaan, Cu/PLA lebih baik berbanding PLA dan ABS, dengan Permukaan 4 mencapai hasil terbaik di bawah keadaan N_2-O_2(0%). Peningkatan dalam kekasaran permukaan mencapai sehingga 24.71% antara Permukaan 4 dan Permukaan 1 pada ketebalan lapisan 0.2mm.. Akhir sekali, kedua-dua keadaan lengai N_2-O_2(0%) dan Ar-O_2(0%) meningkatkan kekasaran permukaan berbanding dengan keadaan tanpa lengai. Analisis SEM menunjukkan bahawa Ar-O_2(0%) menghasilkan jurang udara yang minimum, memudahkan sambungan kuat antara filamen bersebelahan dan mengurangkan kawasan kosong. Kesimpulannya, kajian ini mengesahkan bahawa aplikasi persekitaran gas lengai semasa pencetakan 3D adalah strategi yang sangat berkesan untuk meningkatkan sifat mekanikal dan kualiti permukaan spesimen cetakan. Penemuan ini menawarkan panduan yang penting untuk penyelidikan dan pembangunan masa depan dalam bidang pembuatan tambahan, meningkatkan penggunaan teknik terkini untuk mencapai prestasi bahan dan kualiti yang baik dalam produk cetakan 3D.

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AM	-	Additive Manufacturing
SLM	-	Selective Laser Melting
FDM	-	Fused Deposition Modeling
SLA	-	Stereolithography
CAD	-	Computer- Aided design
ABS	-	Acrylonitrile butadiene styrene
PLA	-	Polylactic Acid
PEI	-	Polyetherimide
ABS-PC	-	Acrylonitrile butadiene styrene-Polycarbonate
ASTM	-	American Society for Testing and Materials
NIST	-	National Institute of Standards and Technology
TGA	-	Thermal gravimetric analysis
SLS	-	Selective Laser Sintering
Cu/PLA	-	Polylactic-reinforced copper
SEM	-	Scanning Electron Microscope

LIST OF SYMBOLS

L	=	Total initial length
ΔA *or* A_{CAD}	=	Different in Area or Area from dimension
T *or* T_0	=	Initial temperature
ΔH *or* H_{CAD}	=	Changes in height or height from dimension
A *or* A_0	=	Initial surface area
D	=	Distance between two points
ΔL or	=	Different in length over initial length
$\frac{\Delta A}{A}$	=	Different in surface area over the initial surface area
σ	=	Stress
E	=	Modulus of elasticity
ε	=	Strain
R_a	=	Surface roughness

LIST OF PUBLICATION

JOURNAL PAPER

1. Che Mat, M.A., Ramli, F.R., Sudin, M.N., Herawan, S.G., and Alkahari, M.R. The effect of tensile strength and surface roughness by varying oxygen level in 3D printer chamber. *Jurnal Tribologi, Vol 33, pp. 80–96 (2022)*.

CONFERENCES ATTENDED

1. Che Mat, M.A., Ramli, F.R., Sudin, M.N., Herawan, S.G., Mat, M.S., Alkahari, M.R. (2022). The Effects of Varying Oxygen Concentrations on Tensile Strength and Surface Roughness of 3D Printer. *Proceedings of the 7th International Conference and Exhibition on Sustainable Energy and Advanced Materials (ICE-SEAM 2021).*

2. Che Mat, M.A., Ramli, F.R., Alkahari, M.R., Sudin, M.N., Abdollah, M.F., Mat, S. Influence of layer thickness and infill design on the surface roughness of PLA, PETG and metal copper materials. *Proceedings of Mechanical Engineering Research Day 2020, pp. 64-66, December 2020.*

CHAPTER 1

INTRODUCTION

1.1 Background of the Project

Fused Deposition Modeling (FDM) is a widely used additive manufacturing technique where thermoplastic filaments are melted and deposited layer by layer to create 3D objects. It is classified among additive manufacturing methods and is gaining popularity among researchers and industry professionals for study and development purposes. Additive manufacturing techniques enable the production of intricate shapes and structures with efficient material management, reducing waste and numerous other benefits compared to traditional manufacturing methods, which are increasing in popularity (Kristiawan et al., 2021).

Fused Deposition Modeling (FDM) is a popular technique in additive manufacturing, known for its ability to produce complex geometries with a wide range of materials (Acierno and Patti, 2023). Nevertheless, due to the complexity of the FDM process, identifying the optimal parameters can pose a challenge, leading to a notable impact on the quality and material properties of the final product.

FDM also has disadvantages that require further consideration, with the primary drawback being its low strength attributed to the weakened interlayer bond formed between layers. This limitation has impeded the utilization of this 3D printing technology to produce functional parts. (Yasa and Ersoy, 2020). In their study, Lederle et al. (2016) observed that oxygen under high-temperature conditions leads to material breakdown in ABS due to oxidation mechanisms. Oxidative reactions primarily influence the polybutadiene phase, which contains active double bonds, resulting in a substantial strength loss. This effect becomes particularly apparent when the finished surface of the 3D-printed component undergoes bending or alteration.

In addition, FDM-printed parts may have a coarse surface finish, necessitating post-processing methods to refine their appearance and enhance performance. The layer-by-layer deposition technique inherent to FDM printing produces visible layer lines, which can compromise the surface finish and dimensional accuracy of printed parts. Consequently, FDM's suitability for end-use applications is restricted. Moreover, temperature variations in the surroundings during 3D printing may result in uneven distribution between adjacent printing layers, leading to shrinkage and warping. Therefore, a controlled and enclosed build environment is essential to minimize the occurrence of warping and shrinkage in FDM (Kuo et al., 2021).

Mazlan et al. (2018a) researched to enhance strength, surface roughness, and warping deformation limitations in FDM parts. They employed pre-processing techniques, such as optimizing process parameters. Additional in-processing methods, such as the integrated pressing mechanism, adaptive slicing and vacuum system (Maidin et al., 2018), along with post-processing methods such as chemical vapour treatment (Sunay et al., 2020), have demonstrated improvements in FDM-printed parts. Therefore, to fully harness FDM's potential for functional component fabrication, the exploration of more innovative or refined techniques is essential.

1.2 Problem Statements

While FDM remains a widely adopted 3D printing technique due to its ease of use and affordability, research on enhancing its capabilities using inert gas flooding within the printing chamber remains relatively limited. Mazlan et al. (2018a) demonstrated an increase in tensile strength and surface roughness when employing inert gas-assisted 3D printers compared to