Faculty of Mechanical Engineering

DEVELOPMENT AND PERFORMANCE ANALYSIS OF A NOVEL 4 AXIS MPAW-BASED WAAM SYSTEM

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DECLARATION

I declare that this thesis entitles “Development and Performance Analysis of a Novel 4 Axis MPAW-based WAAM System” 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 Doctor of Philosophy.

Signature :......... ....

Supervisor Name :......... ....

Date :......... ....

DEDICATION

I want to dedicate this thesis to the Almighty Allah, who has created me in an intelligent fashion and given me the ability and strength to carry out this research and writing of this dissertation. Besides, specially dedicated to my lovely parents for their continuous support, encouragement, and patience.

"There is no power nor strength except by Allah."

ABSTRACT

Additive Manufacturing (AM) is a process that creates free-form structures by layering material. Wire Arc Additive Manufacturing (WAAM) is a promising technique for fabricating large-scale metal structures with high deposition rates among the several AM techniques. However, excessive heat input in conventional arc welding used for WAAM has drawbacks in deposition resolution and surface finish. The use of non-consumable tungsten electrodes requires an external wire feeding, and the need to supply from the same direction during deposition has led to complicated path planning. Most WAAM systems used industrial robots as the motion mechanism but it increases the cost required to fabricate the metallic structure. This study aims to develop a low-cost 4-axis micro plasma arc welding (MPAW) based WAAM system. The systems incorporate 4 axis 3D printer as a motion mechanism and MPAW as a heat source to address this issue. The study develops the 4-axis 3D printer which consists of three linear axes (X-axis, Y-axis, Z-axis) and one rotational axis (A-axis). The advantage of using MPAW is the current usage is less or equal to 20A current. Additionally, an external wire feeding system is integrated with 4 axis MPAW-based system to deliver wire material. The wire feeding angle from the preliminary finding was found of 60° to deliver constant metal bridging transfer mode. The optimising design of the experiment (DOE) for single bead deposition was performed using response surface methodology (RSM) to achieve the maximum bead height, *H* and bead width, *W*, and minimum bead roughness (Ra). The optimal input parameter was 36.63 mm/min of wire feed speed, 64.86 cm/min of welding speed, and 100% welding pulse with desirability of 0.537. Multilayer linear structure is successfully fabricated with the optimal parameters and its morphology, microstructure, and mechanical properties were investigated. The result indicated the morphology feature is free from cracks and apparent defects or pores. The microstructure of multilayer linear structure exhibits a non-uniform microstructure and mainly consists of the cellular dendrite, columnar dendrite, and equiaxed dendrite. The transformation occurs due to the multiple thermal cycle and reduction of the temperature gradient. The average microhardness value is highest at the bottom at 209.152 HV and gradually decreases at the middle and increases towards the top. Moreover, the ultimate tensile strength is also highest at the bottom with an average of 670.082 MPa. The result of the fractured image through SEM revealed a fine dimple structure formed at the bottom and large dimple structure at the top region. Compared with other WAAM processes, the 4-axis MPAW-based WAAM system tensile strength is the highest. Lastly, the 4-axis MPAW based WAAM system was validatd by low dimension difference percentage errors between CAD model and fabricated structures (rectangular, cylinder, curve, and vase). Thus, the study successfully develop the new low-cost 4-axis MPAW-based WAAM system. A better understanding of single-layer deposition, multilayer deposition, and the effect on structure fabrication is supported.

PEMBANGUNAN DAN ANALISIS PRESTASI PEMBAHARUAN SISTEM 4 PAKSI MPAW BERASASKAN WAAM

ABSTRAK

Pembuatan aditif (AM) adalah proses menghasilkan struktur bentuk bebas menggunakan lapisan bahan. Pembuatan aditif wayar arka (WAAM) membolehkan pengeluaran cepat komponen logam yang bersifat tinggi nisbah beli dan jual daripada beberapa teknik AM. Walau bagaimanapun, pemindahan haba yang tinggi dalam kimpalan arka konvensional berasaskan WAAM mengakibatkan kelemahan dalam resolusi pemendapan dan kekemasan permukaan. Penggunaan elektrod tungsten yang bukan guna habis memerlukan suapan wayar luar dan perlu dihantar dari arah yang sama semasa pemendapan telah membawa kepada perancangan laluan yang rumit. Kebanyakan sistem WAAM menggunakan robot industri sebagai mekanisma pergerakan tetapi ia meningkatkan kos yang diperlukan untuk menghasilkan struktur logam. Kajian ini bertujuan untuk membangunkan sistem 4-paksi kimpalan arka mikro plasma (MPAW) berasaskan WAAM berkos rendah. Sistem ini terdiri dari percetakan 3D 4-paksi sebagai mekanisma pergerakan dan MPAW sebagai sumber haba untuk mengatasi masalah ini. Kajian ini membangunkan pencetak 3D 4 paksi terdiri daripada tiga paksi menegak (paksi-X, paksi-Y, paksi-Z) dan satu paksi putaran (paksi-A). Selain itu, suapan wayar luar disepadukan bersama sistem 4-paksi MPAW berasaskan WAAM untuk menghantar bahan wayar. Sudut suapan wayar dari kajian awal didapati ialah 60° untuk pemindahan bahan logam secara mod berterusan. Parameter pemendapan lapisan tunggal reka bentuk optimum (DOE) yang dioptimumkan berdasarkan kaedah tindak balas permukaan metodologi RSM dan ANOVA untuk mencapai tinggi maksimum (H), lebar maksimum (W) dan permukaan kasar minimum (Ra) lapisan tunggal. Parameter kemasukan yang optimum ialah 36.63 mm/min kelajuan suapan wayar, 64.86 cm/min kelajuan kimpalan, dan 100% nadi kimpalan, dengan kehendak 0.537. Struktur berbilang lapisan berjaya dihasikan dengan parameter optimum dan ciri morfologi, struktur mikro, sifat mekanikalnya telah dikaji. Hasilnya menunjukkan ciri morfologi bebas dari rekahan, kecacatan atau liang yang ketara. Mikrostruktur berbilang lapisan pula mempamerkan struktur tidak seragam yang terdiri daripada dendrit selular, dendrit kolumnar, dan dendrit equiaxed. Perubahan ini terjadi disebabkan kitaran haba berbilang lapisan dan pengurangan kecerunan suhu. Nilai purata kekerasan mikrostruktur berbilang lapisan adalah tertinggi di bahagian bawah pada 209.152 HV dan berkurangan secara beransur-ansur di bahagian tengah dan meningkat ke bahagian atas. Selain itu, kekuatan tengangan juga tertinggi di bahagian bawah dengan purata 670.082 MPa. Hasil dari imej patah melalui SEM mendedahkan struktur lesung pipit halus terbentuk di bahagian bawah dan struktur lesung pipit besar di bahagian atas. Berbanding dengan proses WAAM yang lain, kekuatan tengangan sistem 4-paksi MPAW berasaskan WAAM adalah yang tertinggi. Akhir sekali, sistem 4-paksi MPAW berasaskan WAAM disahkan dengan ralat peratusan perbezaan dimension yang rendah di antara model CAD dan sruktur yang dihasilkan (segi empat tepat, silinder, lengkungan, dan pasu). Oleh itu, kajian ini berjaya membangunkan sistem 4-paksi MPAW berasaskan WAAM berkos rendah baharu. Pemahaman yang lebih baik tentang enapan satu lapisan, enapan berbilang lapisan, dan kesan ke atas fabrikasi struktur juga disokong.

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LIST OF SYMBOLS

^{o}	-	Angle
CO_2	-	Carbon dioxide
^{o}C	-	Celsius
R	-	Growth rate
H	-	Height
%	-	Percentages
P	-	Penetration
$\boldsymbol{p}$	-	Pulse
G	-	Temperature gradient
$\boldsymbol{v}$	-	Welding Speed
W	-	Width
$\boldsymbol{f}$	-	Wire feeding speed

LIST OF ABBREVIATIONS

AM	-	Additive manufacturing
ANOVA	-	Analysis of variance
BJ	-	Binder Jetting
BTF	-	Buy-to-Fly
CAD	-	Computer-Aided Design
CNC	-	Computer Numerical Control
CTWD	-	Contact Tube to Working Distance
CMT	-	Cold Metal Transfer
DED	-	Directed Energy Deposition
EBF^3	-	Electron Beam Free Form Fabrication
EBM	-	Electron Beam Melting
FDM	-	Fused Deposition Modelling
GMAW	-	Gas Metal Arc Welding
GTAW	-	Gas Tungsten Arc Welding
LMD	-	Laser Metal Deposition
LENS	-	Laser Engineer Net Shaping
MJ	-	Material Jetting
ME	-	Material Extrusion
MPAW	-	Micro Plasma Arc Welding
PAW	-	Plasma Arc Welding
PBF	-	Powder Bed Fusion

RSM	-	Response Surface Methodology
SOD	-	Standard of Distance
SEM	-	Scanning Electron Microscope
SL	-	Sheet Lamination
SLM	-	Selective Laser Melting
STL	-	Standard Tessellation Language
VP	-	Vat Photopolymerization
VP	-	Variable Polarity
WAAM	-	Wire Arc Additive Manufacturing
WLAM	-	Wire Laser Additive Manufacturing

LIST OF PUBLICATIONS

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Bronze award "4-Axis Micro plasma 3D Metal printer/Metal Additive Manufacturing", Malaysia Technology Expo 2022.