Design and Development of a Metal Additive Manufacturing System Using Metal Inert Gas (MIG) Technology

P.P.A. Manishi
manishiprabasha@gmail.com

P.L.P.M. Mandis
pamudimendis@gmail.com

J.G.D.J. Dinusara
dehanjayawardena@gmail.com

S.C.P. Ephraims
senel.ephraims@gmail.com

K.S. Amarasekara
kasun.amarasekara.net@gmail.com

A.G.C.O. Atadaswala
chalanganamax@gmail.com

Thamasha Samarasinghe
thamashas@uom.lk

Eranga De Silva
ahteranga@uom.lk

Nirosh Jayaweera
niroshj@uom.lk

Department of Mechanical Engineering
University of Moratuwa
Sri Lanka

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I. Introduction

Metal Additive Manufacturing (AM) has advanced significantly due to its ability to fabricate complex geometries with reduced waste and lead time, proving economic viability compared to conventional manufacturing methods [1]. Among metal AM technologies, Wire Arc Additive Manufacturing (WAAM) is particularly suited for large-scale components, leveraging the arc welding process for high deposition rates. WAAM is cost-effective due to its use of inexpensive welding wire and standard equipment.

Gas Metal Arc Welding (GMAW), a widely used WAAM technology, uses an electric arc to melt a continuously fed wire, depositing material layer by layer under shielding gas. It is classified as Metal Inert Gas (MIG) and Metal Active Gas (MAG) depending on the type of shielding gas used. However, its main limitations include reduced dimensional accuracy, difficulties in fabricating complex geometries, and the need for extensive post-processing [2].

The primary objective of this study is to develop a low-cost metal AM system that incorporates a readily available welding technology, MIG, thereby offering small-scale manufacturers and developing nations an alternative solution for fabricating and repairing complex metallic components.

II. Literature Review

Several studies have focused on developing low-cost metal AM systems using WAAM technologies and have identified various limitations in their approaches. For instance, Rosli et al. [3] have reported non-uniform mechanical properties in MIG-based WAAM systems. Similarly, a study by G.C. Anzalone et al. [4] has emphasized shortcomings in electromechanical and control systems based on their WAAM system which integrates Gas Tungsten Arc Welding (GTAW) technology.

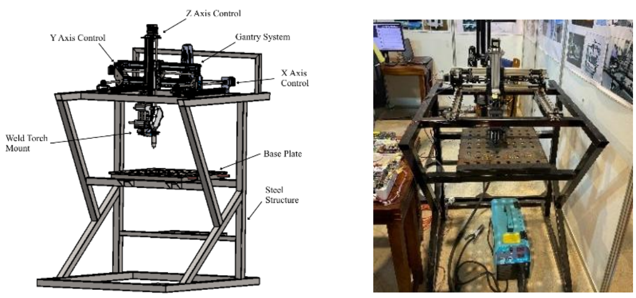
These studies collectively highlight the need for more refined process control strategies to ensure consistent quality in metal components manufactured using WAAM systems. They also depict that moving from documented parameter effects to integrated systems with real-time monitoring and adaptive control is a key challenge. This study directly addresses this challenge with a MIG-WAAM system that integrates gantry control, arc monitoring, and thermo-mechanical simulation to enhance process stability.

III. Methodology

The system was designed to be cost-effective, modular, and based on open-source hardware with custom designs and firmware to facilitate easy modification and future expansion. A structured, multi-phase methodology integrating design, simulation, experimental optimization, and control system was followed in the development process.

A. System Design and Integration

A modular 3-axis gantry system was designed and fabricated using steel and aluminium profiles to ensure structural rigidity. The motion control system was built around an Arduino Mega 2560 with a RAMPS 1.4 shield, running custom-configured Marlin firmware. A custom-designed, heat-resistant torch mount ensured precise positioning, integrating a RETOP MIG-275 welding power source. The workflow was automated by generating toolpaths from CAD models using Ultimaker Cura Slicer, with post-processing to adapt the G-code for welding commands. Fig. 1 displays the CAD model and the developed prototype of the system.



(a) (b)

Fig. 1. (a) CAD Model of the Machine; (b) Developed Prototype

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B. Process Parameter Optimization

The effects of weld parameters—voltage (V), current (A), wire feed rate (WFR), and travel speed (TS) on deposition quality were studied through manual trials, empirical observations, and iterative tuning. Their influence on bead width, height, penetration depth, and surface uniformity was evaluated to identify optimal parameter combinations. A practical operating envelope was then established and applied in experimental trials, consisting of a voltage of 20–25 V, a current of 120–140 A, a WFR of 6–8 m/min, and a TS of 1000 mm/min.

C. Simulation-Driven Process Validation

A thermo-mechanical simulation of the WAAM process was conducted using ANSYS Additive DED module to validate the experimental work. Multi-layer straight and circular builds were modelled, with transient thermal analysis predicting temperature gradients and cooling rates. Using the global heat-source method, power input was applied as temperature boundary conditions with total energy defined as,

$$E = Q \cdot \Delta t \quad (1)$$

where Q is arc power and Δt the layer time. A coupled structural analysis was then used to estimate residual stresses and deformation, identifying potential warping regions. The simulation outcomes were used to refine process parameters prior to trials and were later verified against experiments to ensure agreement on trend and magnitude. Analysis revealed that the peak melt-pool temperature exceeded 1290 °C, and heat was conducted into the base plate, resulting in significant inter-layer thermal gradients.

D. Development of Control and Monitoring Systems

To enhance process stability, a novel control system was designed and partially invented. The torch activation was synchronized with the gantry motion using the extruder signal from the RAMPS board. A theoretical model relating arc current to arc length was developed in MATLAB. A closed-loop control system was designed using Simulink to adjust the torch height based on real-time current feedback, to maintain constant arc length. The system's performance was validated by fabricating test specimens, including single-layer straight lines, multi-layer (up to 5 layers) rectangular walls, and circular paths using ER70S- mild steel wire.

IV. Results and Discussion

After fabrication, the printed samples underwent visual and dimensional inspection. Height accuracy decreased with increasing layers due to error accumulation, heat buildup, and distortion. Minimum spatter occurred within the operating current range, whereas high travel speeds or low wire feed rates caused undercut and wavy edges. Bead geometry was measured and compared with the 3D model, and simple cross-sectional checks revealed no inclusions, porosity, or other defects. The desired quality was achieved only within a narrow operating window, with deviations producing irregular bead formation. Simulation results aligned well with experiments in both trend and magnitude, confirming its value for deposition planning and parameter tuning.

(a) (b) (c)

Fig. 2. Samples of printed components (a) single layer circular prints; (b) cross-section of one sample; (c) multi-layer print

TABLE I. Geometric Results of Printed Components

Test no.	Single-layer lines		Circular component	
	Length (mm)	*Width* (mm)	*Diameter* (mm)	*Width* (mm)
1	51.42	4.67	50.42	3.96
2	51.93	4.85	50.44	3.8
3	52.61	4.65	49.9	3.63
Standard Deviation	0.9583	0.1429	0.2427	0.1462

Table I presents the geometric specifications of the printed single-layer line and circular specimens. The CAD models defined line dimensions of 50 x 5 mm and circular dimensions of 50 mm in diameter and 4 mm in width, both with a height of 2 mm. In both cases, the printed layer heights closely matched the input values.

V. Conclusion

The developed system successfully fabricated simple components with satisfactory accuracy and structural integrity, as confirmed through design, simulation, and experimental validation. This work demonstrates the feasibility of a low-cost, modular metal AM system using MIG technology integrated with a 3-axis gantry platform. While the study did not encompass an assessment of advanced metallurgical properties and did not resolve all limitations of WAAM, it establishes a solid foundation for accessible metal AM solutions and offers direction for future research.

VI. Future Work

Future research should prioritise the dynamic regulation of process parameters through advanced closed-loop control systems. Thermal management may be enhanced by incorporating suitable thermal management systems. Additionally, detailed metallurgical analyses are required to identify defects and assess the mechanical behaviour of components fabricated using MIG-based WAAM.

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