

Proceedings of the 58th CIRP Conference on Manufacturing Systems 2025

Monitoring framework for physical knowledge exploration in wire-based directed energy additive manufacturing (w-DEDAM)

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Abstract

Monitoring in wire-based directed energy deposition additive manufacturing (w-DEDAM) is crucial for ensuring part quality and process stability. It aids in optimising process control, enhancing efficiency, and minimising material waste. Additionally, monitoring provides valuable documentation for regulatory compliance and supports maintenance by tracking equipment performance. Effective monitoring and relevant control enhance process reliability, reduce scrap, and ensure the production of high-quality components. However, current monitoring systems in w-DEDAM face significant challenges. Key issues include a lack of standardisation in monitored variables, leading to inconsistent data and interpretation. Many existing monitoring systems often focus on the adjustable “knob” variable measurements rather than critical factors that more accurately represent physical process conditions. This narrow focus can fail to capture essential aspects of process explanation and part quality. Furthermore, there is a deficiency in integrating monitoring data with digital modelling and qualification methods, limiting the ability to use real-time data for comprehensive process optimisation and predictive analysis. Addressing these gaps is crucial for advancing system effectiveness. In this research, key process variables will be defined and explained to enhance process understanding. A knowledge-driven monitoring framework will be proposed to tackle the issues of standardisation and relevance of monitored parameters, ensuring that critical variables are accurately captured and utilised. Additionally, the study will introduce a commercial industry monitoring software based on this framework, which is currently used in the industry. This software integrates the proposed approach, offering a robust solution for real-time monitoring and process control, thus addressing existing limitations and supporting improved process optimisation and digital modelling.

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Peer-review under responsibility of the scientific committee of the International Programme committee of the 58th CIRP Conference on Manufacturing Systems

Keywords: Wire-based directed energy deposition additive manufacturing (w-DEDAM), Monitoring system, Digitalisation.

1. Introduction

Additive manufacturing (AM) is defined as the process of joining materials to make parts from 3-dimensional (3D) computer-aided design (CAD) models, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies [1]. w-DEDAM uses an electric arc, electron beam, or laser as the energy source to melt the

metal material or alloy wire to deposit large, fully dense, 3D, near-net-shape metallic components [2].

The deposition process encompasses several physical phenomena. The feed wire is melted by the energy source, generating droplets. These droplets are then transferred to the melt pool that is also created by the energy source, where fluid flow occurs within the melt pool. Simultaneously, heat transfer takes place among the melt pool, feed wire, deposited part, and

the surrounding environment. Ultimately, as the energy source moves forward, the melt pool solidifies, forming the as-deposited bead. In this deposition process, to ensure the process stability and deposition quality, monitoring methods are frequently used to gather information on process conditions. Common monitoring targets include factors such as melt pool condition [3], interlayer temperature [4] and deposited geometry [5,6], alongside other physical parameters illustrated in Fig. 1, using a plasma arc as an example of the energy source.

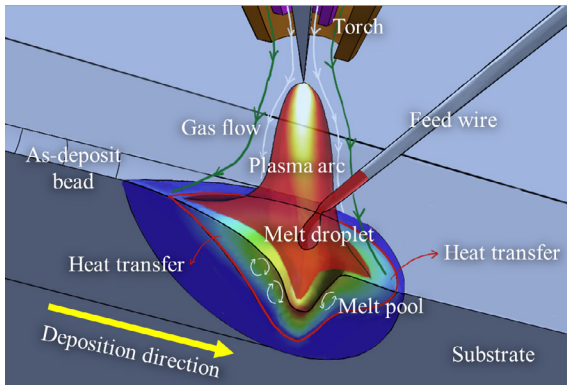


Fig. 1. Common physical factors in the w-DEDAM deposition process

The multi-physics nature of the deposition process requires the use of various monitoring devices and digital models to gather sufficient data for analysis. The combined information and algorithms can then be applied for knowledge extraction [7], process control [2], and part quality assurance [5].

During the monitoring process, data and information are generated from various sources, which are then analysed with digital models. Monitoring frameworks can be employed to coordinate these data sources and digital models, enabling the monitoring data to yield more valuable insights. Various frameworks have been proposed by different research groups for specific purposes. Xu et al. [8] developed a multi-sensor monitoring framework for wire arc additive manufacturing (WAAM). Such frameworks can accommodate data and information including torch position information, oxygen concentration level, arc current, voltage, and cloud point data from laser profilometer. Process related physical factors such as defects, molten pool condition, cooling rate etc. can be extracted from the acquired data. Reisch et al. [9] proposed a multivariate monitoring framework for WAAM, which integrates various sensor data alongside material data and the control for the WAAM system. This framework enables the realisation of multiple tasks, including defect detection and closed-loop control. However, it lacks an efficient mechanism to represent the interactions of physics-related information. Gaikwad et al. [10] introduced the concept of digital twins in AM. This framework integrates monitoring data from photodetector sensors with computational models, enhancing the accuracy of flaw prediction during the deposition process. The digital twin relies solely on a machine learning model to detect flaws, without employing a physics-based approach to identify the root causes of the flaws in relation to process parameters.

The current monitoring frameworks encounter several challenges. 1). Inconsistencies in monitoring variables across

different AM systems, which pose difficulties in data interpretation and communication among stakeholders. 2). Insufficient integration and communication among monitoring devices, existing AM knowledge bases, and digital models, which limits the full exploitation of the data's potential [8]. 3). The absence of an efficient mechanism to elucidate the relationship between system input parameters ("knob" parameters) and output physical factors, thereby impeding precise control over the manufacturing process [8,9].

Therefore, this paper proposes a monitoring framework based on w-DEDAM knowledge. The variables involved in the deposition are determined and defined to facilitate a uniform understanding. These variables are then categorised, and a model capturing the interactions among them is proposed to support physical knowledge extraction. Furthermore, physical knowledge is incorporated into the monitoring framework to coordinate the interplay among various monitoring devices and digital models, enabling the generation of more comprehensive information and knowledge.

2. Monitoring variables in w-DEDAM

In this section, the monitoring variables considered in the framework are outlined and defined to guarantee standardization for w-DEDAM. Subsequently, the variables are grouped according to the distinct roles they play in the deposition process, allowing for a more structured organization.

2.1. Variable selection and definition

As a multi-physics process, many physical factors and phenomenon would influence the deposition process as illustrated in Fig. 1. In this study, physical process is considered central to the analysis of the variables. The variable selection focuses on two key aspects: factors that influence the physical process and factors that reflect the properties of the deposited part, which result from the physical processes. The factors that can affect the physical process include the deposition parameters, the properties of feed wires, the setup of the system and the environmental factors. These factors would collectively influence the deposition system, producing a system response, which is the actual output of the deposition system. The part, as the product of the deposition system, serves as the indicator of the physical processes. The part properties encompass the variables that can characterize the beads, including the morphology and the thermal properties. In total, 42 variables are selected and shown in Table 1.

The system parameter settings group mainly consists of process parameters the system operators input into the system. They are typically set in the w-DEDAM systems during the process planning, determined either by the system operators' experience or w-DEDAM related control algorithms.

The hardware setup variables of the w-DEDAM system are established during the configuration and assembly of its hardware components such as the energy source, positioner and wire feeder. These components are critical to the deposition process, as they could influence the physical phenomenon occurring during the deposition.

Table 1 Key variables of w-DEDAM and definition

Category	Variable Name	Definition
System parameter setting	set current	the current in the plasma welding energy source set by the user
	set shielding gas flow rate	the shielding gas flow rate set by the user
	set shielding gas composition	the composition of the shielding gas chosen by the user
	set plasma gas flow rate	the plasma gas flow rate set by the user
	set travel speed	the speed that the energy source moves with respect to the workpiece
	set contact tip to working distance	the distance between the contact tip to the welding point
	set torch angle	the angle between the torch and the working piece set by the user
	interval time	the time elapsed between successive layer completions
	set wire feed speed	the velocity that the feed wire is fed to the energy source
Hardware setup variable	bead centre distance	the centre distance between adjacent beads
	nozzle diameter	the diameter of the nozzle outlet
	electrode geometry	the diameter of the electrode
	electrode setback	the distance between the tip of the electrode and the tip of the nozzle
	wire feed angle	the angle between the wire feeding nozzle and the substrate/torch travel direction
	wire feed direction	the direction of wire feeding relative to the torch's travel direction
Feed wire property	initial wire tip position	the relative position of the wire tip to the centre of the energy source
	nozzle diameter	the diameter of the nozzle outlet
	electrode geometry	the diameter of the electrode
	electrode setback	the distance between the tip of the electrode and the tip of the nozzle
	wire feed angle	the angle between the wire feeding nozzle and the substrate/torch travel direction
Environmental factor	wire feed direction	the direction of wire feeding relative to the torch's travel direction
	initial wire tip position	the relative position of the wire tip to the centre of the energy source
	humidity	the humidity at the site of the
	ambient temperature	the environment temperature measured at the site of the deposition
System output	monitored voltage	the voltage measured during the deposition
	monitored current	the measured current of the welder
	monitored shielding gas flow rate	the shielding gas flow rate measured near the torch tip
	arc length	the length of the arc, which is equal to the CTWD
	wire tip position	the spatial position of the melting end point position
	torch tip position	the spatial position of the torch tip
	torch angle	the angle between the torch and the working piece
	wire position stage	the distance between the tip of the wire and the melt pool
Physical factor	linear heat input	the energy per unit length input in the melt pool
	volumetric heat input	the energy input into per unit volume of material during the wire melting
	energy density	the amount of charge per unit time that flows through a unit area of a chosen cross-section
	arc heat distribution profile	the pattern that the heat generated from the energy source is distributed
	deposition layer area	the cross-section area of the deposition bead
Part property	oxygen level	the portion of the oxygen in the shielded area
	external morphology	the geometry of the deposited bead, including the dimensions and external defects
	internal morphology	the internal morphology of the bead, including the internal defects such as pores
	as-deposited thermal profile	the thermal state of the deposition, including the thermal profile of the melt pool and the as-deposited bead

In the w-DEDAM process, the feed material is mainly in the form of metal wire. The material properties and characteristics of the feed wire can influence the system parameter settings and, consequently, the physical factors during the deposition. The properties of the wire primarily encompass its geometry and material characteristics.

The environmental factors can indicate the environmental conditions that cannot be manually modified by the system operator but still affect the deposition process.

The system response variables deal with the variables that can indicate the physical output of the w-DEDAM system, including that of the energy source, positioner and wire feeder. These variables can typically be monitored with the sensors attached to the system or can be directly read from the system's interface.

Physical factors are the variables that can be used for physical analysis. These factors cannot be directly monitored, but these variables can be generated from the system output parameters and the existing knowledge about the w-DEDAM process. These variables typically reflect the physical phenomenon of the deposition process.

The deposition properties encompass the variables that can reflect the resultant properties of the physical deposition process, including internal and external morphology, and thermal profiles of the parts. These properties, in the following analysis process, can determine the quality of the deposition product.

3. Knowledge-based monitoring framework

In this section, a monitoring framework embedded with physics knowledge is proposed. The framework is visualised in Fig. 2. The proposed framework operates on three levels. The first level, or “shop level”, focuses on the w-DEDAM system's operations within the workshop. Here, data is grouped into system input factors, which influence system behaviour, and part output factors, the system's end products. Operators or control algorithms define these system parameters, considering feedstock properties, deposition needs, and prior layer conditions. Monitoring devices capture the system's responses and part outputs, feeding data into the next level.

The second level, or “data level”, organizes and stores information, clarifying relationships among data groups. This

level contains two main components: system response data and part quality indicators. System response data reflects the system's output to input factors, while part quality indicators measure the quality of the deposited parts. Data from monitoring devices must be further processed and analysed, requiring w-DEDAM-specific knowledge to derive actionable insights.

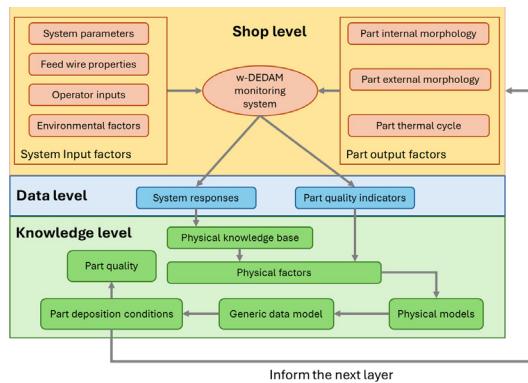


Fig. 2 Monitoring framework with physics knowledge embedded

The third level, or “knowledge level”, manages physics-based insights. Data from the previous level is converted into physical factors (defined in section 2.1) to represent deposition dynamics. The conversion from system monitoring variables to physical factors follows a “Parameter-Response-Factor” mechanism, leveraging combined physical knowledge bases. Through the mechanism, system parameters are converted into monitorable system responses, which are later processed into physical factors with physical knowledge base, providing structured insights into the deposition process. This approach enhances process planning and facilitates closed-loop control, thereby optimising the performance and operational consistency of the w-DEDAM system. Subsequently, these factors are then fed into physics-based models (e.g., FE or CFD models), where calculations reveal complex interactions. The generic data model, created from this process, organizes information from physical models to accurately reflect part deposition conditions. This information collaboratively allows operators to adjust system input factors and provide insight about the deposition physical processes. This information will contribute to the deposition of the next level in the workshop.

This monitoring framework links devices, data, and models, supporting advanced applications in deposition, as described in section 4.

4. Applications

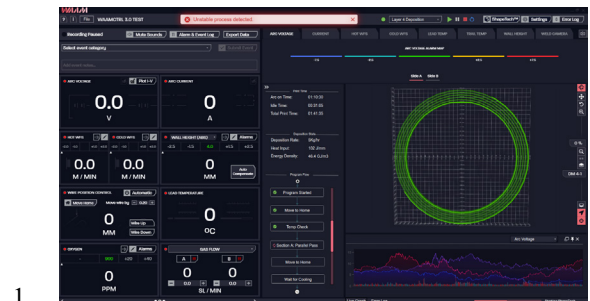
The proposed monitoring framework enables the handling of tasks encountered in real industrial scenarios, including the monitoring, analysis, and control of the w-DEDAM process. This section introduces various applications that utilise the monitoring framework.

4.1 WAAMCtrl

In this application, a software case of a w-DEDAM process monitoring, and control solution (WAAMCtrl) is presented. The interface of the software is shown in Fig. 3.

Developed within the WAAM3D framework [11], WAAMCtrl integrates multiple sensors to collect relevant near real-time variables involved in the framework. These variables include monitored current, monitored voltage, wire feed speed, travel speed, layer height, oxygen level, shielding gas flow rate, and part thermal profile [11]. Using a client-server architecture, data is regularly gathered from sensors, computer numerical control (CNC) machines, and power sources, then displayed for operators with a unified interface. Input variables (e.g., set current) and output variables (e.g., monitored voltage) are presented with color-coded indicators to highlight deviations, aiding efficient process monitoring.

In w-DEDAM, process parameters significantly impact bead shape, quality, and deposition stability [12]. WAAMCtrl employs live charts to display the historical relationship between data and variables, while three-dimensional visualization tracks the tool path, torch, and sensor positions. The deposition conditions are further monitored using in-process camera feeds, providing information on the melt pool, heat distribution, arclength, wire position, and torch angle. System response variables, such as arc efficiency, are converted into system-independent factors (e.g., heat and material input) for in-process control and post-deposition analysis.



1.

Fig. 3 WAAMCtrl Process Monitoring and Control Interface

WAAMCtrl combines advanced sensors, machine learning models, parameter prediction algorithms, and precise robot control to regulate key deposition parameters like wire position, build height, gas flow, and interlayer temperature, all critical to bead shape and microstructure formation. Faults like wire sticking or gas flow issues are managed by an error notification system that logs critical errors and presents them to the operator based on urgency.

4.2 ShapeTech

ShapeTech is a surface profiling software designed to generate a digital representation of a scanned geometry, which is integrated in WAAMCtrl. Part properties, particularly the external morphology-such as the geometric dimension of the as-deposited bead-can be captured with this technique. It

comprised of two components: a collection program for aggregating and processing data streams, and a visualisation application for analysing the point cloud of a scanned part. The ShapeTech Collection software interprets distance measurements and mirror angle information from a coherent range-resolved interferometry (Co-RRI) sensor [13], synchronising robot positional data collected in WAAMCtrl [11] during the data collection cycle. ShapeTech processes the acquired data packet, applying a trigonometric function to calculate and interpolate the Co-RRI distance data into a list of surface points. These points are mapped against the robot positional data, which is also included as system output in the monitoring framework variables, allowing the collection software to output an array representing the surface as a point cloud for visualization for future analysis.

The scanned surface is viewed and analysed using the ShapeTech visualisation software, where each deposited layer is marked as an individual point cloud and is mapped to a scalar value by using colour representation. Fig. 4 shows an example of the interface, with the scalar bar (left of the image) indicating an expected wall height of 3 mm. This approach enables effective interpretation of the generated point cloud, facilitating the determination of deformities, such as peaks and craters that may occur during the deposition.

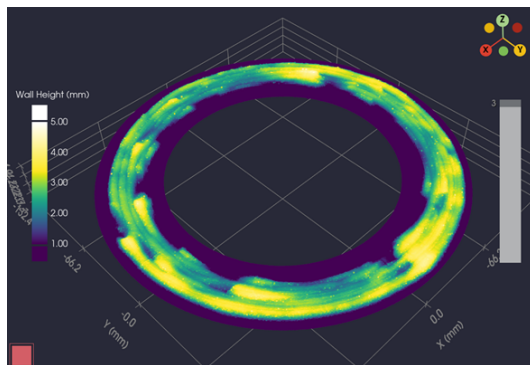


Fig. 4 ShapeTech Visualisation of a scanned layer

4.3 Wall height compensation

Automated interlayer wall height compensation [2] for w-DEDAM is one of the key strategies for control and part quality. In most deposition processes, deposition only based on CAD have difficulty guaranteeing constant layer heights in real industrial situation, due to the uncertainties associated with the manufacturing process including working environment, operator's manipulation and deposition times. Process parameters such as the wire feed speed, monitored current or travel speed, are closely linked to obtaining a firm and constant wall height involved in the bead external morphology profile [14]. Iteration or variation of these parameters generates a delay time or transition period [15], which introduces small irregularities in the deposition height. Accurate wall height control and compensation require precise and efficient measurement of the deposition geometry. In this wall height compensation strategy, ShapeTech, as described in Section 4.2,

facilitates real-time monitoring of wall height variations in the w-DEDAM process.

A series of control points need to be generated as an indication of the deposited wall height. The peak or higher points detected across the deposited layer can be marked as the control points. Real-time wall height data are compared with the target wall height, allowing for the calculation of the differences. Taking into account such difference and the original path planning, an optimised height for the next layer is derived, subsequently forming the basis for a revised path planning strategy, where an appropriate and varied process parameters are applied to each wall region to gradually compensate for wall height. The compensation can normally be achieved within two to three layers. This strategy is further reinforced by the fundamental process parameter settings, which allow corrections in real time during deposition. The operation window is shown in Fig. 5.

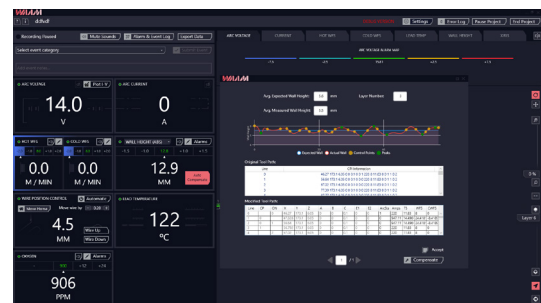


Fig. 5 Wall height compensation in WAAMCtrl

4.4 Auto wire position control

During deposition, quality control is essential for managing the microstructure and minimizing defects like cracks and bumps. In w-DEDAM, keeping the wire at an optimal height helps prevent splashing and poking, ensuring deposition quality. A custom tool was developed to control wire position automatically, using frame-by-frame video tracking of key elements such as the wire, melt pool, droplets, and arc.

One challenge was achieving a feasible frame rate for live video segmentation and tracking, essential for real-time wire adjustments. The tool also needed flexibility to adapt to varying video angles and quality. The solution involves using an image/mask pair with the live video feed for segmentation, allowing easy file swaps to suit different scenarios and improving adaptability. Data preparation includes a tool for processing video, enabling frame selection along the timeline and using the Segment Anything Model (SAM) and insights from the TrackAnything model to identify and track multiple objects in both forward and backward time. This approach created suitable image/mask pairs from weld camera footage.

The methodology uses the XMem [16] model to initialize the inference core, employing an image/mask pair to track and segment objects. Each frame from the weld camera is segmented to monitor the wire, melt pool, droplets, and arc, with the main goal of determining the wire's position relative to the melt pool for real-time height adjustments. Dust, fumes, and particles on the camera lens can reduce video quality, so a

parallel wire position control method uses real-time sensor data, specifically time-series voltage data, to address this issue. Future plans include integrating image- and voltage-based controls with adjustable weighting for optimized decision-making. This approach improves precision and adaptability in deposition quality control, supporting more efficient and reliable manufacturing systems. The operation window is shown in Fig. 6.

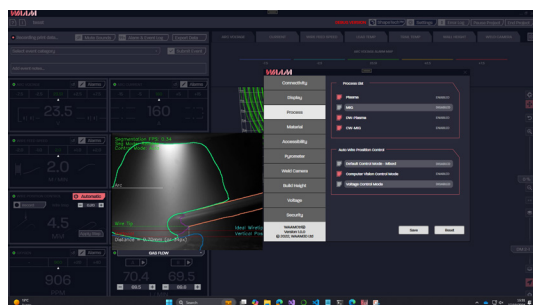


Fig. 6 Auto wire position control in WAAMCtrl

5. Discussion

The implementation of the framework allows for the realization of real-industrial scenarios applications including the visualization of the key variables during the deposition, real-time monitoring and analysing of the deposition processes and control over the deposition parameters. These applications enable enhanced insights for the system operators and more precise control over the deposition process, thereby improving the quality of the deposition. Also, the framework outlines a potential guideline for the collective operation of digital models alongside monitoring devices. Data from the monitoring variables can mitigate the uncertainty that exists within both the digital models and the deposition process. However, there still exists shortage during the implementation of the monitoring framework in real deposition scenarios. Since only limited monitoring methods are involved, not all the variables in the monitoring framework are utilised. In future, more physical factors should be considered in the framework for a better representation of the deposition process. Also, other methodologies such as the implementation of digital models can be introduced in the future. More physics-based digital models, such as FE models can be included to enhance the analysis capabilities of the framework.

6. Conclusions

In this paper, different key variables involved in the w-DEDAM process are defined and classified. A w-DEDAM monitoring framework incorporating physical knowledge is proposed, indicating the relationships between monitoring devices, monitoring data, and physical models. In the proposed framework a universal factor interaction mechanism is proposed to indicate the relationship between different groups to separate the factors occurred during the system operating process and the physics-based analysis process, so that the knowledge base to support both processes can be better developed and organized. Applications based on the proposed

framework are then introduced to indicate the functionality potential of the framework.

Acknowledgements

The authors would like to express their gratitude to Engineering and Physical Sciences Research Council (EPSRC) (EP/W025035/1, Thermal monitoring instrumentation for metal additive manufacturing - PYRAM) for supporting aspects of this research.

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2025-06

Elsevier

<https://doi.org/10.1016/j.procir.2025.03.048>

Chen L, Lasisi S, Vives J, et al., (2025) Monitoring framework for physical knowledge exploration in wire-based directed energy additive manufacturing (w-DEDAM). Procedia CIRP, Volume 134, June 2025, pp. 193-198. 58th CIRP Conference on Manufacturing Systems 2025, 13-16 April, 2025, Enschede, The Netherlands