SOLUTION APPROACHES FOR THE EFFICIENT MODELLING OF THE LAYER BUILD-UP IN THE WAAM MANUFACTURING PROCESS USING SMOOTHED PARTICLE HYDRODYNAMICS

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ABSTRACT

Within Additive Manufacturing (AM) technologies, Wire Arc Additive Manufacturing (WAAM) stands out as a particularly promising process variant. WAAM enables the efficient production of large metal structures and offers significant advantages over traditional processes, especially in the field of repair welding.

A key component for optimizing the WAAM process is simulation, particularly in relation to the concept of a virtual factory. A digital twin could significantly accelerate the wire-and-arc-based AM manufacturing process, especially regarding development, optimization, and certification.

Developing a precise simulation model is crucial to correctly map a weld's geometric shape. In the presented work, Smoothed Particle Hydrodynamics (SPH) is used to develop a model that simulates multiple weld beads building on each other – an area that is not yet fully established due to complex physical interactions and the enormous computing resources required.

The focus of the work is on heat and mass transfer during the WAAM process, aiming to create a model that calculates interactions within a geometry of numerous layer structures while significantly reducing calculation time. The proposed approach fully accounts for mass and heat transfer in the cathode area, while droplet formation and detachment are captured by an equivalent model for more efficient use of computing resources.

The concept for accelerated calculation incorporates a coarse mass discretization and the neglect of a direct resolution of the anode area. Accordingly, the model focuses on the processes in the cathode area concerning the weld to be formed. A side effect of this concept are local deviations in the weld geometry arising from surface tension models in the SPH formalism, affecting global component geometry.

The potential of the model for predicting the temperature field could be demonstrated in the simulative reproduction of an eccentric pin as an industrial reference product. However, there is still no satisfactory agreement between the calculated geometry and the real component. While geometric agreement requires further calibration, the temperature field prediction shows strong consistency with the industrial process. Calculation time still holds potential for improvement.

This work makes a significant contribution to the further development of simulation methods in the field of WAAM and provides valuable information for improving process control and increasing efficiency.

Keywords: WAAM, simulation, SPH, heat and mass transfer, substitute models

INTRODUCTION

Additive Manufacturing (AM) technologies for metals have gained increasing attention in recent years due to their potential for resource-efficient, flexible, and customized production. Among the various AM methods, laser-based and electron beam-based processes offer high precision but are often limited by low deposition rates, high equipment costs, and a narrow range of processable materials, as powder-based feedstocks are not yet widely established in industrial applications. These methods are particularly suitable for micro-scale investigations, such as the study of microstructural evolution [1], but they remain technologically immature in large-scale manufacturing contexts.

In contrast, arc-based processes – specifically Wire Arc Additive Manufacturing (WAAM) – enable high deposition rates and benefit from low system complexity and cost. WAAM is based on Gas Metal Arc (GMA) welding technology, an arc welding process using a continuously fed consumable wire electrode. The major advantage of GMA welding process lies in its high proportion of welding processes used in industry, which means that a wide variety of certified filler wire materials are commercially available, making WAAM an attractive choice for industrial-scale applications.

Wire-and-arc-based AM has demonstrated notable advantages in terms of targeted material usage, cost-efficiency, and flexibility in design, supporting tailored solutions for both new part production and repair applications. Its potential is evidenced by successful implementations in industrial contexts, such as the repair of high-value components [2], cladding applications including the reinforcement of shell geometries [3], and even the fabrication of hybrid material systems. Nevertheless, recent reviews emphasize the relevance for the analysis of stress development and distortion, with a focus on macroscale simulations in WAAM [4].

Recent contributions from our research partners have advanced the simulation of WAAM processes, focusing on heat transfer modelling using finite element methods [5], as well as the numerical prediction of microstructure and hardness evolution [6]. Moreover, economic aspects such as life cycle assessment [2] and green supply chain management strategies [7] underscore the increasing demand for sustainable solutions in additive manufacturing.

Despite the progress, WAAM still faces several challenges. These include limited contour accuracy, complex thermal behaviour, intricate material responses, and non-trivial path

planning requirements [8]. Given the multitude of interacting process parameters, experimental investigation of every influencing factor is not only time-consuming but often infeasible. While academic studies have explored geometric prediction at the level of individual weld beads or small-layer constructs, these models are rarely suitable for industrial use due to excessive computation time and resource demands.

Physically accurate modelling of the bead geometry remains a major computational challenge, as it requires capturing a wide range of complex phenomena. Numerical methods, although capable, are often pushed to their limits. Simplified approaches – such as the use of equivalent heat sources (e.g., the Goldak model and its extensions using volumetric discretization, [9]) or the activation of predefined mesh elements – are commonly employed to reduce complexity. However, the feedback effect of the existing bead geometry on subsequent layers has only been explicitly modelled in select studies, notably by [10], while in most cases it is either indirectly addressed or merely discussed as a future perspective.

The objective of this study is to transfer a previously developed and experimentally validated SPH-based model [11] for Gas Metal Arc (GMA) welding to the multilayer WAAM process and to demonstrate its applicability using real industrial production data. For the production of the demonstrator component, a highly electrically and mechanically controlled GMA welding process, Cold Metal Transfer® (CMT®), was used. CMT® is a controlled short-circuit GMA welding variant characterized by cyclic wire retraction, enabling reduced heat input and controlled droplet transfer [11]. The capability of the base model to capture the CMT® specific process phases, short-circuit and arc phase, was demonstrated in [11].

All process parameters used in the simulation – including current, voltage, wire feed rate, inter-layer timing, and torch trajectory – were directly extracted from the robot program of an industrial wire-and-arc-based AM production system operated by our project partner Guaranteed.

The overarching goal is the creation of a digital twin of the WAAM process. In this context, computational efficiency is not merely a numerical aspect but a decisive industrial requirement: only if simulation time remains within economically acceptable limits can the model be used for production planning and process preparation.

INDUSTRIAL FRAMEWORK AND DIGITAL TWIN CONCEPT

The present study was conducted in close collaboration with the industrial partner Guaranteed, a company specializing in large-scale wire-and-arc-based additive manufacturing. The investigated demonstrator component was produced on an industrial robotic WAAM system using certified production parameters.

The simulation model does not rely on artificial test cases or parameter fitting. Instead, the robot program (G-code) used for manufacturing the real component served directly as simulation input. The torch trajectory, average current, average voltage, and wire feed rate were extracted without modification and implemented in the SPH framework.

This approach enables the development of a prototype digital twin of the WAAM process. The objective is not solely the numerical reproduction of bead geometry, but the establishment

of a predictive simulation tool that, after further calibration, can support industrial process design and production preparation.

METHODS

The methods for the consideration of physical phenomena in a GMA welding process were developed within the frame of SFB 1120 “Precision Melt Engineering”, a Collaborative Research Centre funded by the German Research Foundation (DFG), focusing on the physical understanding and control of melt-based manufacturing processes.

In general, the simulation concept of the GMA welding process pursued in SFB 1120 is based on dividing the domain into three areas: anode, arc and cathode (Fig. 1). This is done by selecting particles based on their geometric positions. Further selection criteria (temperature, surface, orientation, etc.) allow the particles to be assigned to the appropriate models for heat input, replacement model for acceleration due to the Lorentz force or solidification model.

Grid-based numerical methods (Euler methods) are widely used in the simulation of manufacturing pro-cesses [12] [13] [14]. In the event of a significant change in topology in the simulation area, the use of Euler methods results in additional complexity associated with the algorithms for determining the free surface. These methods do not require further development, as they already represent the state of the art. However, it is also known that such simulations are very time-consuming.

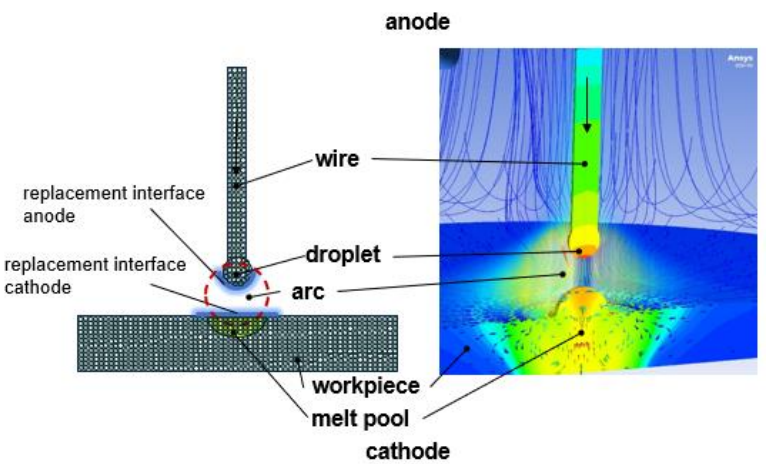

Fig. 1: Division of the simulation area into three domains

Mesh-free Lagrangian methods solve these problems using native approaches. The mass is carried by the interpolation points themselves and cannot be lost. The mesh is also replaced by a point neighbourhood, for which efficient data structures exist. This allows topology

changes to be handled implicitly. The Smoothed Particle Hydrodynamics (SPH) method is one such method that has proven itself in physics and has recently also found application in engineering. It impresses with its simplicity, efficient computability and stability. The SPH framework SPlisHSPlasH [15] is being developed at RWTH Aachen University. It already offers modern methods for simulating fluids, elastic bodies, highly viscous materials and coupling with rigid bodies [16–18].

CONCEPT 1: DROPLET FORMATION AND DETACHMENT CONSIDERATION

The method for WAAM-simulation using SPH was developed based on the work of SFB 1120 and on the platform called SPlisHSPlaSH. This platform includes solvers for general physical phenomena such as heat and mass transport, models for taking surface tension and temperature-dependent viscosity into account, and the definition of kinematic and thermal boundary conditions. Welding process-specific models were integrated that allow the electromagnetic effect and the arc effect to be considered:

- surface heat input through the processes in the anode and cathode layers
- volumetric heat source due to Joule heating
- volumetric acceleration due to the Lorentz force (drop separation)

The compensation models for the physical phenomena are activated in accordance with the CMT® process phases: heat input through the electric arc in the CMT® process arc phase and material transport or droplet detachment through the Lorentz force acceleration model in the short-circuit phase. The replacement model is based on Ampère's force law and relates the disc radii of the conductor through which the current flows. Joule heating is active in both phases. A detailed description of the model was introduced in [11].

On this basis, a dynamic process is mapped with the interaction between the variable wire feed, the heat input from the arc and the melting and detachment of the material. Short-circuit detection and thus the wire movement direction is based on the melt pool or solidification profile. The determined curves for average wire feed and current are set as target values. The phase duration is extrapolated according to the short-circuit detection, using the last value from the average cycle until the phase change.

The result shown in [11] were generated using the following SPH and real process parameters:

Table 1: SPH parameters for the CMT® process simulation.

Particle Ø	mm	0.2
Particle count	-	300,000
Simulation duration	h	2
Process duration	s	4
Number of layers	-	1

CONCEPT 2: ONE PARTICLE PER DROPLET WITH A SURROGATE MODEL OF THE ANODE AND CATHODE REGION

Extrapolation of the required computing resources shows that a simulation of the WAAM process using the current approach would not be feasible within a reasonable time frame. An acceleration concept was therefore developed in which the anode processes of droplet formation and detachment are not directly mapped, but the heat input and melting are also taken into account. The concept concentrates the computing power on the heat transfer and mass transfer in the workpiece or in the structure formed by the many layers. The approach envisages that the phenomena in the anode are recorded by substitute models until the moment the droplet is free to fly. Fig. 2 demonstrates the area for the activation of pressure and thermal solver. Furthermore, it is assumed that an SPH particle takes on the size of a droplet.

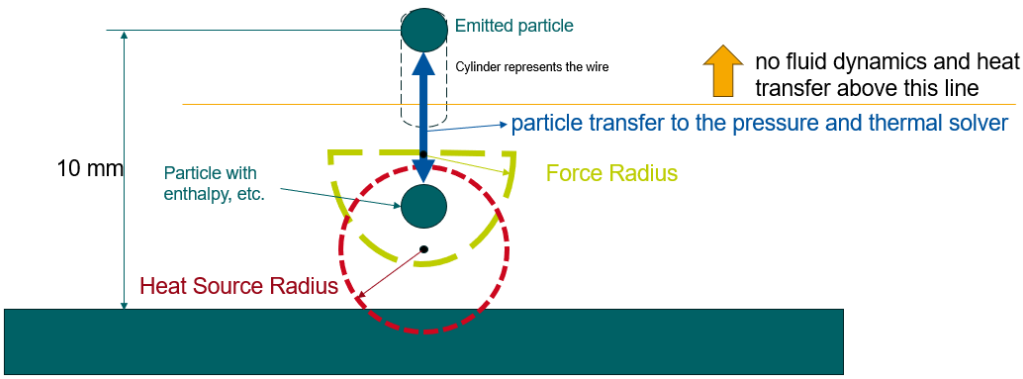

Fig. 2: Surrogate models of anode and cathode layers effects

This eliminates the need to represent the anode for the simulation of the WAAM process. This state is clearly visible in the Fig. 2: the droplets or particles are inserted according to the wire feed speed and heated by the heat input model of the arc effect. The speed of the droplets is determined using the Lorentz force acceleration model, whereby, the ratio of the arc radii between the anode and cathode is assumed to be 1:2. According to the developed substitute models, the momentum of the droplet corresponds to the acceleration of a CMT® short-circuit transition.

RESULTS

With these assumptions a virtual part consisting of 20 layers was simulated, Fig. 3. The simulation parameters are listed in Table 2. This approach shows a significant acceleration resulting in 1 min of process per 1 h of calculation time compared to 2 s of process per 1 h calculation time and an acceleration factor of ≈ 30.

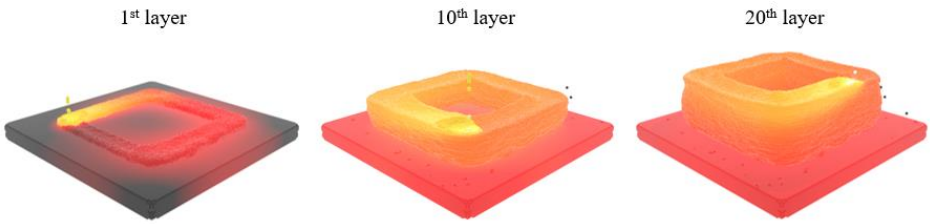

Fig. 3: Example for material deposition and layer build-up capability of the "one particle per droplet" concept, 70x70x5 mm substrate, 40x40 mm deposition path

Table 2: Simulation parameters for the concept "one particle per droplet", as shown in Fig. 3. The particle count increased during the simulation from 24,000 to 59,000 due to continuous layer deposition. Since the surrogate approach assigns one SPH particle per droplet, the number of particles directly reflects the accumulated deposited material.

Particle Ø	**mm**	**1**
Number of particles	-	
Start of simulation	-	24,000
End of simulation	-	59,000
Simulation duration	h	6
Process duration	s	450 (7.5 min)
Number of layers	-	20

For the development of a digital twin, Guaranteed suggested a component from its own practice and provided the robot program for manufacturing this component, Fig. 4, a. The burner path, consisting of 18 layers, and the welding parameters for the manufacturing process were extracted from the robot program, Fig. 4, b. Fig. 4, c Presents a time step of the manufacturing process using a reconstructed surface. The final geometry of the component as well as the temperature field at a time step in the cooling phase are shown in Fig. 4, d, using particle-based raw data.

The calculation time for the simulated production of the component was 130 hours, while the real manufacturing process required approximately 40 minutes, Table 3. All computations were performed on the CPU 2X Intel Xeon Gold 6326. This comparison is not intended as a limitation but as an evaluation of digital twin feasibility. In industrial process planning, simulation time represents a critical performance indicator. The presented surrogate approach enables, for the first time within our SPH framework, the simulation of an 18-layer industrial

WAAM component using real production parameters. Without the introduced acceleration strategy, such a simulation would not be computationally feasible.

It should be noted here that the total simulation time also includes the cooling process, i.e. approx. 20 minutes of real time. In total, one hour of real process time (WAAM + cool down) was calculated within 130 hours, Table 3. During the transient calculation, the system status was exported every second with the corresponding calculated physical variables. This export frequency results in a memory requirement of 60 GB.

The simulation environment was prepared for the input of external data. The G-code-based robot program used to manufacture the demonstration component serves as the basis. The average values for the heat source were extracted from this program: average current and average voltage. The wire feed was also taken from an average value. The torch movement from the program is specified in the simulation environment in the form of a *.csv file.

Since the torch has equidistant steps for the layers and the power source regulates the arc distance, additional effort is necessary to adopt the emitter height during the simulation.

Also, the speed of the drop must be controlled so that it corresponds to the CMT® process.

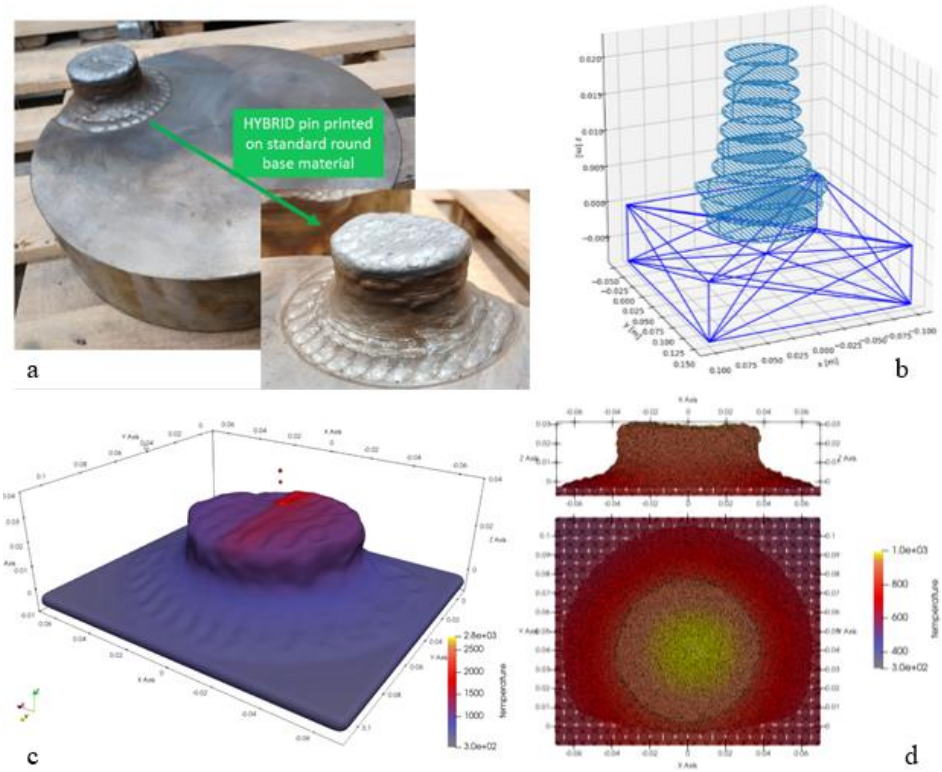

Fig. 4: Demonstrator component digital twin results. a: manufactured eccentric pin, b: torch path for the robot program, c: simulation time step for the material deposition process, d: final geometry and time step in the cooling phase of the simulation

Table 3: SPH parameters for a WAAM process simulation.

Particle Ø	mm	1
Number of particles	-	
Start of simulation	-	84,000
End of simulation	-	330,000
Simulation duration	h	130
Process duration	s	2,200 (36.6 min)
With cooling time	s	3,344 (55.7 min)
Number of layers	-	18

DISCUSSION AND OUTLOOK

The developed simulation model demonstrates the successful transfer of a validated SPH-based GMAW welding model to multilayer wire-and-arc-based additive manufacturing. Using unmodified industrial production parameters and the original robot trajectory, an 18-layer demonstrator was simulated. This constitutes a decisive step toward a physics-based digital twin of the WAAM process. By predicting bead geometry across multiple layers, it enables early-stage evaluation and optimization of process parameters, thereby reducing reliance on costly and time-consuming trial-and-error testing. A systematic parameter variation study is beyond the scope of this work, as the primary objective is the transfer of a validated welding model to an industrial WAAM digital twin under fixed production conditions.

The primary achievement of this work lies not only in geometric prediction but in demonstrating computational feasibility under industrial boundary conditions. The surrogate concept (“one particle = one droplet”) represents a necessary abstraction to make multilayer wire-and-arc-based AM simulation practically usable for process preparation and optimization.

The authors see the simulation framework presented here as a module or intermediate step toward a fully comprehensive digital twin, in which the current state does not yet provide a precise geometric match, but nevertheless allows the temperature field, especially inside the component, to be used for analyzing material behavior.

Additional predictive capability will come from incorporating a density-change model that accounts for the metal’s density in the liquid, transition, and solid phases. Including phase-dependent density variations in the simulation can improve the prediction of the solidification process, residual stresses, and final geometry, thereby enhancing the model’s value for process design and qualification.

Despite these advances, computational cost remains a barrier to widespread industrial adoption. Additional performance optimizations are necessary to render the model viable in time-critical production settings.

A particularly promising acceleration strategy is adaptive discretization, which concentrates computational resolution in regions with steep physical gradients. This approach reduces overall computational load while preserving accuracy. Building on this, a natural next step is to adopt a hybrid strategy: apply high-resolution, adaptive discretization in zones that

require strict accuracy, while using the “one particle per droplet” concept in areas where no critical changes in part formation are expected. Such a combined approach enables efficient use of computational resources by matching the level of model fidelity to local process needs.

From a software-architecture standpoint, future deployment will benefit from modularizing the computational backend and decoupling it from the user interface. Such encapsulation facilitates integration into diverse software ecosystems or digital twins without extensive reengineering and permits incremental improvements to the simulation engine without disrupting user-facing components.

Transient simulations generate vast amounts of data, presenting challenges for storage and interactive visualization. A server-centric workflow – storing datasets on high-capacity servers and leveraging server-side rendering for visualization – can mitigate these issues. Visualization can be streamed (e.g., as video) to remote clients, enabling responsive, accessible, and interactive analysis even for large-scale transient simulations.

The main achievements of this work can be summarized as follows:

- Successful transfer of a validated SPH-based GMAW welding model to multilayer WAAM.
- Direct implementation of industrial robot path and production parameters without artificial tuning.
- Simulation of an 18-layer industrial demonstrator component.
- Development of a surrogate modelling strategy enabling digital twin feasibility.
- Identification of remaining geometric deviations and their physical origin within the SPH surface tension formulation.

APPENDICES AND ACKNOWLEDGEMENTS

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