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# Predictive Modelling of Weld Seam Formation for Industrial GMAW Joints Using a Hybrid Simulation Approach


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**Abstract**

We present a simulation framework that unifies the major physical scales of Gas Metal Arc Welding (GMAW) to predict weld seam formation with high fidelity. Over more than a decade, research focused on the development and coupling of models dedicated to electrical circuit behaviour, plasma and arc physics, droplet transfer, weld-pool flow, and solidification. Mesh-based magneto-hydrodynamics (MHD) calculations incorporating the EDACC model resolve the characteristic asymmetric arc attachment in the cathode region, while particle-based SPH methods capture transient droplet detachment, short-arc behaviour, melt-pool dynamics and enthalpy-porosity–based solidification. The hybrid approach quantifies how local evaporation, current density distribution, and metal flows govern weld-pool evolution and weld seam formation. The applicability to industrial welding configurations is demonstrated.



**Keywords**

GMAW, simulation, arc attachment, SPH, hybrid modelling, weld pool dynamics


## 1 Introduction

Gas metal arc welding (GMAW) is one of the most widely used joining technologies in industrial manufacturing due to its high productivity, flexibility, and applicability to a broad range of materials and joint configurations. Despite its industrial relevance, the predictive simulation of weld seam formation remains a major scientific challenge. The process involves strongly coupled physical phenomena, including arc plasma behaviour, heat and mass transfer, droplet detachment, weld pool flow, and phase transformations during solidification, Figure 1. These phenomena span multiple spatial and temporal scales, ranging from fast electromagnetic processes in the arc to slower thermofluid dynamics in the molten metal. A central difficulty in GMAW simulation lies in the interaction between the arc plasma and the weld pool surface. The local temperature of the molten metal governs evaporation, which modifies plasma composition, electrical conductivity, and ultimately the distribution of current density and heat flux at the cathode. This feedback mechanism controls weld pool evolution and, consequently, the resulting weld seam geometry. However, many modelling approaches still treat the arc as a prescribed heat source and therefore neglect the self-consistent plasma-metal interaction.

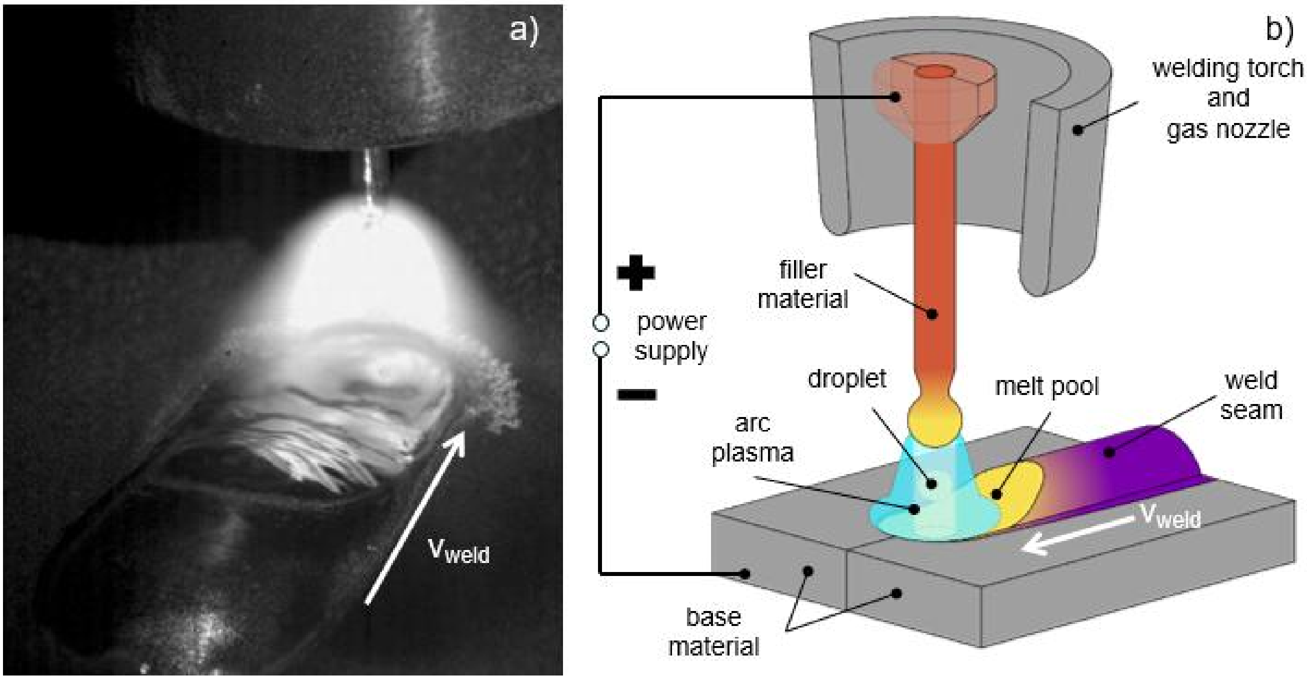



**Figure 1:** left: High-speed footage of the GMAW process clearly shows the rippling of the molten pool and the concentration of the arc intensity in the front portion of the molten pool, right: Schematic diagram of GMAW highlighting key areas and components.

Over the past decades, different modelling strategies have been developed to describe individual aspects of the GMAW process. Early approaches relied on simplified analytical or empirical heat source descriptions [1–4], whereas more advanced models incorporated fluid flow and phase transformation in the weld pool [5,6]. More comprehensive approaches include magnetohydrodynamic (MHD) descriptions of the arc plasma [7–9], while dedicated studies emphasized the importance of metal vapour in determining arc behaviour [10,11]. In parallel, detailed investigations of near-electrode plasma sheath regions provided an important physical basis for describing anode and cathode interactions [12–14]. Despite these advances, a consistent and computationally efficient framework that combines arc physics, droplet transfer, and transient weld pool evolution is still missing. Within the Collaborative Research Centre (CRC 1120), subproject A04 addressed this gap by developing physics-based models for the key subprocesses of GMAW. In particular, the interaction between evaporation and cathodic heat input was systematically investigated, leading to the formulation and validation of the Evaporation Determined Arc–Cathode Coupling (EDACC) model [15–19]. These studies showed that arc attachment and heat input are strongly governed by local evaporation effects and become inherently asymmetric under realistic welding conditions. A further step in the project was the transition from stationary or weakly coupled descriptions towards transient process modelling. In this context, alternative numerical strategies for time-resolved multiphase flow simulation were evaluated [20]. At the same time, Smoothed Particle Hydrodynamics (SPH) was introduced as a promising Lagrangian framework for welding-related free-surface problems. Its applicability was first demonstrated for wire metal transfer in GMAW process variants [21], quantitatively assessed for welding-like thermal flow problems [22], and further supported by related SPH developments for particle impact and free-surface deformation [23,24]. These works established the methodological basis for using SPH to resolve droplet detachment, weld pool dynamics, and evolving free surfaces without remeshing. Based on these developments, a hybrid simulation strategy was established in which Eulerian finite-element approaches are used to resolve arc plasma behaviour, while Lagrangian SPH methods are applied to transient melt flow and weld seam formation. The coupling of both domains through physically based surrogate models enables a predictive simulation framework that combines high physical fidelity with improved computational efficiency.

## 2 Aim of the Investigation

The aim of this work is to develop a predictive simulation framework for weld seam formation in GMAW that consistently captures the key interacting physical phenomena, including arc plasma behaviour, droplet transfer, and weld pool dynamics. To this end, modelling approaches developed over more than a decade within subproject A04 of the CRC 1120 are integrated into a unified hybrid framework. A particular focus is placed on the EDACC model and its influence on heat input distribution, melt pool evolution, and resulting weld geometry. Furthermore, the suitability of a hybrid modelling strategy combining Eulerian finite element methods for arc simulation with Lagrangian Smoothed Particle Hydrodynamics (SPH) for transient free-surface flows is investigated. The developed approach is finally applied to industrially relevant welding configurations to assess its predictive capability.

## 3 Evolution of the Modelling Approach and Key Physical Contributions

### 3.1 Evaporation determined arc–cathode coupling (EDACC)

In gas metal arc welding (GMAW), heat input is governed by the interaction between the arc plasma and the metal surfaces of the consumable electrode (anode) and the workpiece (cathode). The main conversion of electrical energy into heat occurs in the near-electrode regions, whereas the arc column primarily serves as a current-carrying medium, Figure 1. This description applies to arc lengths exceeding approximately one to two wire diameters, where anode and cathode regions remain spatially separated and can be treated as distinct. The anode is typically formed by the molten droplet at the wire tip. Its arc attachment is mainly controlled by plasma processes within the arc column, resulting in a compact and nearly axisymmetric current density distribution. Heat transfer is dominated by ion recombination, supplying energy for melting and droplet formation. Although metal evaporation increases with temperature and alters plasma properties, the anode attachment remains stable and adjusts gradually in size. In contrast, the cathode region (weld pool surface) is characterized by strong plasma-surface interaction under a pronounced potential gradient. Here, heat input and current density distribution are governed by the EDACC mechanism. According to this concept, metal evaporation from the cathode surface determines local plasma properties and thereby controls current distribution. The feedback mechanism can be summarized as follows: local heating enhances evaporation; metal vapour reduces plasma ionization and electrical conductivity; consequently, current is redistributed toward regions with more favourable conditions. Additionally, ionized metal species are accelerated back to the surface, intensifying the plasma-surface interaction. This leads to a highly non-linear and spatially sensitive system. As a result, the cathode coupling is inherently asymmetric, strongly dependent on the local temperature distribution, and dynamically influenced by process parameters such as welding current. Since current density directly correlates with heat flux, this non-uniform energy input governs melt pool flow through thermal and electromagnetic forces. Therefore, the cathode region becomes the dominant factor controlling weld pool shape, stability, and overall process behaviour. Figure 2 illustrates these effects. For a lower welding current (100 A), the current density distribution remains approximately Gaussian and centred near the wire projection. At higher current (400 A), however, the maxima shift towards the weld pool edge, and a symmetric distribution is no longer observed. This demonstrates the transition to evaporation-driven, asymmetric arc attachment as predicted by the EDACC model.

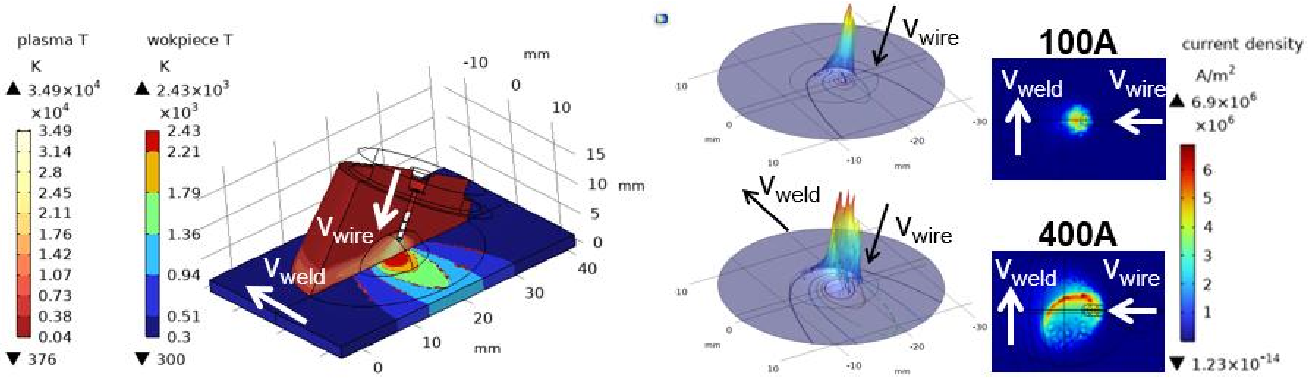



**Figure 2:** Asymmetric current density and heat flux distribution at the cathode predicted by the EDACC model.

### 3.2 Transition to transient modelling and SPH

The coupled multiphysics models demonstrate that key GMAW phenomena - arc dynamics, droplet formation, and rapid solidification - can only be captured consistently in a transient formulation. This requires a numerical approach capable of handling strong topological changes such as droplet detachment, breakup, and coalescence without remeshing. Smoothed Particle Hydrodynamics (SPH), a fully Lagrangian method, fulfills these requirements by representing the continuum with particles carrying mass, momentum, and thermal state. This enables a natural description of free-surface evolution and makes SPH particularly suitable for modelling droplet transfer and weld pool dynamics, Figure 3.

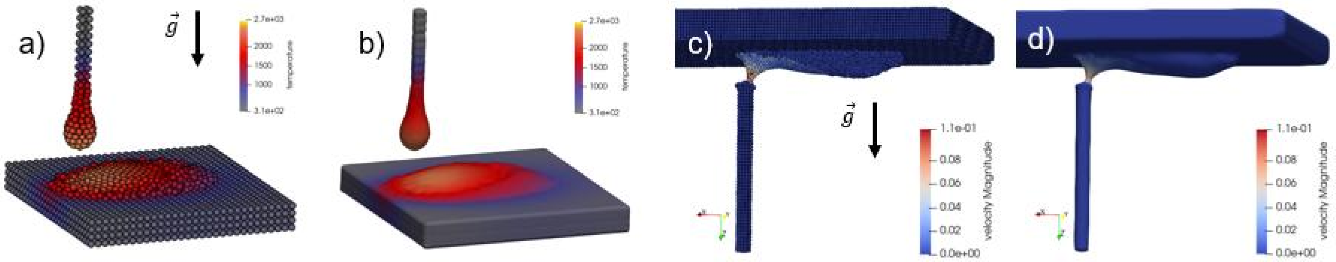



**Figure 3:** SPH simulation of droplet transfer and weld pool dynamics showing strong topological changes and SPH capability for capturing the physics. a) Snapshot of the droplet detachment with the according temperature field, particle representation, b) reconstructed surface representation of a).

The transient welding process is simulated using the open-source framework SPlisHSPlasH [25], which has been extended for welding-specific applications. It allows the import of arbitrary CAD geometries and process data, including current and wire feed rate, enabling time-resolved simulations under realistic conditions. The capability of the framework to capture heat and mass transfer in GMAW is illustrated in Figure 3. Surface reconstruction and interpolation of field quantities are performed using splashsurf [26], providing a continuous representation of particle-based results, Figure 3, b).

### 3.3 Weld seam formation and Solidification

The arc heat source is represented as a surface heat flux distribution acting on the metal surface exposed to the arc. In the numerical implementation, this surface-based energy input is converted into an additional thermal contribution assigned to the SPH particles located at the arc–metal interface. The heat input is applied exclusively to surface particles, ensuring a physically consistent representation of energy transfer from the arc while preserving the particle-based formulation. Surface tension is modelled using two approaches: a curvature-based formulation and a cohesion-based method derived from an effective Lennard–Jones potential. The cohesion-based approach has proven particularly suitable for SPH, as surface tension emerges implicitly from inter-particle forces. This enables a stable and consistent description of interface dynamics, including droplet formation, melt pool deformation, and weld pool shape evolution. Solidification is described using an enthalpy-based formulation with a mushy zone, in which liquid and solid phases coexist. As the solid fraction increases, fluid motion is progressively damped by introducing a momentum sink term in the Navier–Stokes equations. This term represents the Darcy-type resistance of the semi-solid dendritic structure and depends on temperature via the local liquid fraction. The permeability of the mushy zone is evaluated using a Carman–Kozeny relation, linking microstructural evolution to macroscopic flow resistance. This approach allows a consistent description of the transition from liquid flow to solid structure and enables the prediction of weld seam formation within the particle-based framework.

### 3.4 Simulation area decomposition and development of the hybrid framework

The GMAW process involves vastly different time and length scales: electromagnetic and plasma phenomena settle in microseconds and sub-millimetre regions, while heat conduction, fluid flow, droplet detachment, and solidification evolve over milliseconds to seconds across centimetre-scale domains. By exploiting the quasistationary nature of the electromagnetic (EM) and plasma fields, they can be represented with an efficient Eulerian heat-source model that provides steady Lorentz forces and heat fluxes, Figure 4 right). The slower thermofluidic and solidification processes require a Lagrangian description capable of handling large deformations and topological changes. Consequently, a hybrid framework is built in which surrogate SPH models are driven by the Eulerian solutions, using the latter's results to define reduced-order inputs for the particle-based calculations, Figure 4 left).

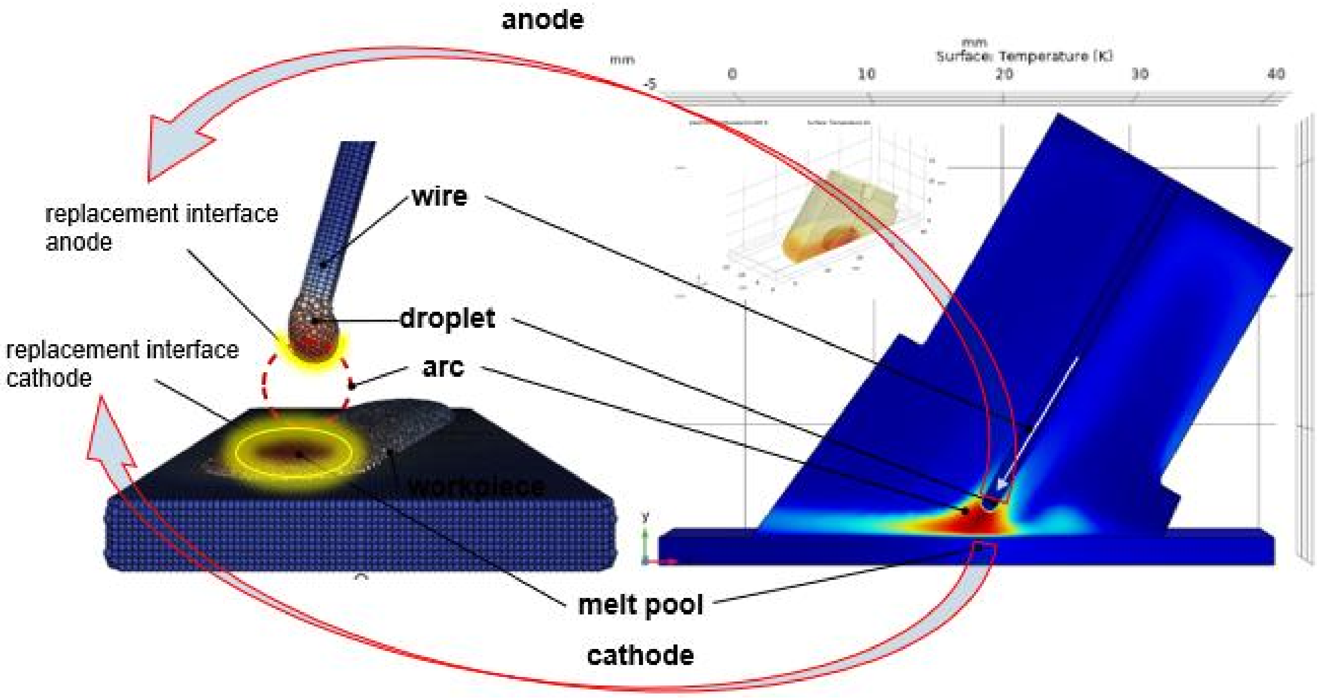
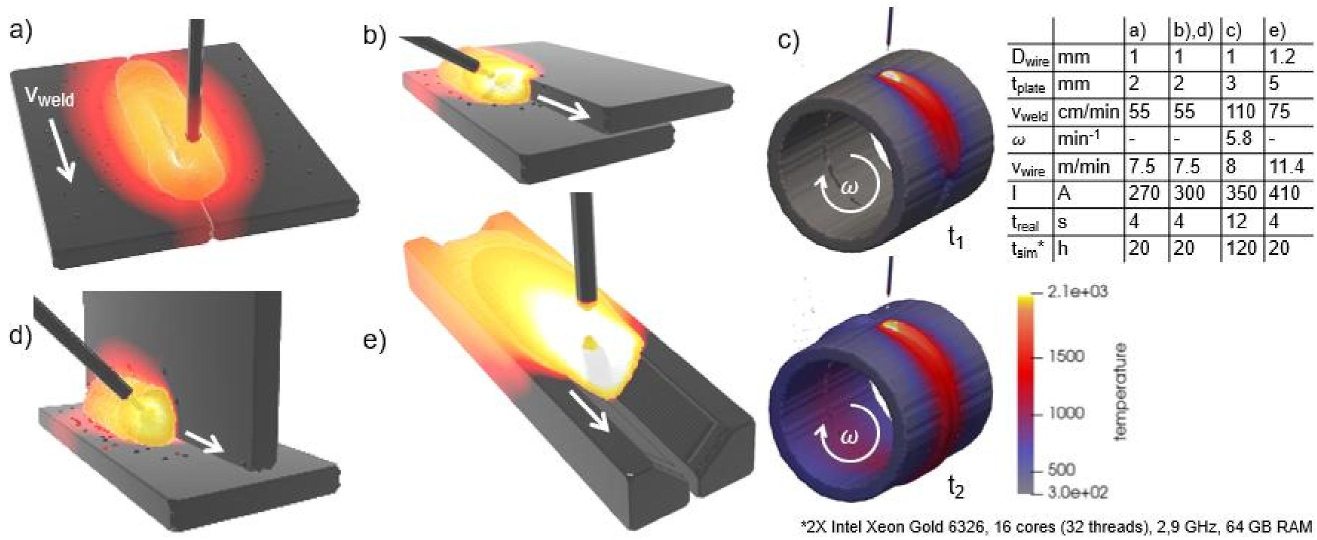



**Figure 4:** Hybrid modelling concept combining right) Eulerian arc simulation and left) Lagrangian SPH weld pool simulation.

## 4. Results for Industrial Welding Configurations

Industrial welding demands a modelling tool that can reproduce the full range of GMAW process variants used in production-controlled short-circuit (SC) welding, pulsed spray-arc (impulse) processes, and conventional continuous arcs - by simply varying the input parameters (current and wire feed waveform, travel speed, shielding-gas flow, etc.). In addition, the model must be capable of representing the actual workpiece geometries, joint configurations, and seam-preparation conditions (e.g., gap size, edge bevel, root opening) that are encountered in practice. To answer engineering questions such as productivity, bead geometry, and defect susceptibility, the model must therefore resolve the key physical phenomena that differentiate these modes: rapid arc-plasma dynamics and associated Lorentz forces, intermittent droplet detachment and metal-vapor generation, and the resulting transient heat-transfer and solidification behaviour. Moreover, the framework ought to accommodate a wide spectrum of material properties - and, ideally, material mixtures as well - because these dictate the mechanical-technological performance of the final construction; however, the current implementation is limited to homogeneous base materials and does not yet support dissimilar-material welds. By meeting these requirements, the hybrid framework offers a predictive, parameter-driven virtual laboratory for the optimisation of real-world welding processes. With the presented simulation framework, a wide range of possibilities is enabled, since many of the physical effects necessary for simulating the gas metal arc welding process are considered. Figure 5 illustrates the simulation results for industry-relevant welding tasks. The models are capable not only of reproducing safe, validated process variants but also of depicting process limits, such as a through-weld shown in Figure 5 a). Additionally, both the torch, represented by the wire in Figure 5 a), b), d) and e), and the workpieces, shown in Figure 5 c), can be moved in the simulation. For GMAW-based additive manufacturing processes, in particular Wire and Arc Additive Manufacturing (WAAM), the new aspect is the focus on the deposition of many layers and on massive constructions.




| | | a) | b),d) | c) | e) |
|---|---|---|---|---|---|
| $D_{wire}$ | mm | 1 | 1 | 1 | 1.2 |
| $t_{plate}$ | mm | 2 | 2 | 3 | 5 |
| $v_{weld}$ | cm/min | 55 | 55 | 110 | 75 |
| $\omega$ | $min^{-1}$ | - | - | 5.8 | - |
| $v_{wire}$ | m/min | 7.5 | 7.5 | 8 | 11.4 |
| I | A | 270 | 300 | 350 | 410 |
| $t_{real}$ | s | 4 | 4 | 12 | 4 |
| $t_{sim}$* | h | 20 | 20 | 120 | 20 |

**Figure 5:** Application of the hybrid model to industrial welding configurations: a) butt joint, cooling phase, end of the solidification process, b) lap joint, wire inclination 60 °, snapshot of the weld seam formation process, c) pipe weld, snapshot of the weld seam formation with moving workpiece, d) T-joint, wire inclination 45 °, e) butt joint, Y-groove configuration, elevated material thickness and filler material deposition.

The actual challenge of this process is the path planning and the influence of the path on the energy input and resulting mechanical and technological properties. Therefore, there is a great need for a transient prediction of the component geometry and temperature. A new concept was developed to tackle this task: the focus on the workpiece and the deposited weld seam structure rather than on the droplet formation and detachment process. The concept concentrates the computing power on the heat and mass transfer in the workpiece or in the structure built up by numerous layers. The approach envisages that the phenomena in the anode up to the time of free flight of the droplet are captured by substitute models. Furthermore, the approach includes the assumption that an SPH particle assumes the size of a droplet. This eliminates the need to represent the anode for the simulation of the WAAM process. The droplets or particles are inserted according to the wire feed speed and heated by the heat input model of the arc effect. An explicit resolution of the wire and droplet detachment process is not necessary for the questions regarding material deposition.

## 5 Discussion

Several physical and modelling aspects remain open and define promising directions for future work. From a material science perspective, the temperature dependence of surface tension in the high-temperature range is still insufficiently known. Since surface tension and its gradients govern capillary and Marangoni-driven flow, improved data and models are essential for a more reliable prediction of weld pool dynamics and final seam geometry. On the arc side, the role of anode evaporation and the resulting vapour fraction in the plasma has not yet been fully resolved. A more detailed description of anode vapour transport and its interaction with the plasma could refine the prediction of arc attachment patterns and local heat input. In addition, the effect of droplet impingement on the molten pool deserves further attention: the strong local cooling induced by the droplet is expected to promote a more concentrated arc attachment in the pool centre and thereby induce additional acceleration of the liquid metal. From a numerical standpoint, dynamic discretization in SPH (e.g. adaptive refinement and coarsening of particles) would allow a better resolution of local phenomena at comparable computational cost. Incorporating volumetric contraction and an extended material model covering the liquid-solid transition would further enable the prediction of solidification defects such as shrinkage cavities or porosity. The current hybrid Eulerian–SPH framework is structured in a modular way, so that these additional physical and numerical features can be integrated stepwise in future developments.

## 6 Summary

This paper presents the concept development, implementation and application results of a hybrid Eulerian-Lagrangian simulation platform for GMAW over a period of more than ten years. At the outset of CRC 1120, no fully coupled numerical description of GMAW was available. During the first funding period, we therefore developed an in-house Fortran code for transient, fully coupled magnetohydrodynamic (MHD) simulation of the arc–melt pool system including free-surface deformation. For a simplified joint configuration (blind seam in a symmetric butt joint in PA position), 1 s of process time required about 48 h of computation, which severely constrained parametric studies and practical applications. In the second funding period, the focus shifted from demonstrating full coupling towards understanding and modelling the dominant driving mechanisms of melt-pool flow and surface energy input. Within this analysis the cathode layer was identified as the key link in the physical chain between plasma and the liquid metal. A dedicated model was formulated to couple the arc action to the MHD behaviour of the weld pool. In the same context, the foundation for including metal evaporation in the arc attachment region was laid and ultimately led to the EDACC model. Based on the insights and experience gained, a phenomenological splitting strategy was established. Short-time-scale phenomena (plasma, electromagnetics, layer processes) are now computed with mesh-based finite-element methods, whereas large-scale and slow processes such as heat transfer, droplet detachment, and weld-pool dynamics are resolved with a particle-based (SPH) approach. This separation of time scales avoids solving all processes within a single monolithic model and instead allows pre-computing plasma and electromagnetic fields as input for the transient SPH simulations. Furthermore, the evaporation-controlled attachment has proven to be so dominant that parameterized representations of its effects can be formulated for the surrogate model and used in the SPH simulations. As a result, the plasma itself does not need to be resolved in the transient calculation. As a result, stationary 3D simulations including the EDACC model can today be carried out with commercial solvers within a few hours. In parallel, the advanced SPH framework enables particle-based simulations of arbitrarily complex, industrially relevant joint topologies, with typical runtimes of about 4 h per 1 s of process time. Consequently, subproject A04 has significantly broadened both the range of accessible physical phenomena and the spectrum of practically relevant welding configurations, while achieving an overall speed-up of approximately one order of magnitude compared to the initial in-house Fortran solution. The combination of physically based arc modelling using the EDACC concept and transient SPH simulation of weld pool dynamics enables a realistic prediction of weld seam formation. The results highlight the importance of asymmetric arc attachment and evaporation effects for heat input distribution. The developed approach provides a robust basis for future applications in process optimization and digital twins of welding processes.

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**Conflict of Interest**

The author declares no conflict of interest.

**Data Availability Statement**

The data supporting the findings of this study are available on reasonable request at http://hdl.handle.net/21.11102/c894c7f3-e06b-4ea9-914c-8defc7a97340.

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