CognitivaTech: Ingeniería de Software Inteligente y Sistemas Adaptativos. 2024; 1(1):2
doi: 10.63688/cognitivatech.v1.i1.2

ORIGINAL

Development of a computational simulation environment for GMAW based on coupled physical models

Desarrollo de un entorno de simulación computacional para procesos GMAW basado en modelos físicos acoplados

Mayra del Rosario Matute Morlas[1]

[1] Universidad Estatal de Milagro. Milagro, Ecuador.

Submitted: 12-02-2024 | Revised: 17-03-2024 | Accepted: 26-04-2024 | Published: 28-04-2024

Corresponding Author: Mayra del Rosario Matute Morlas

ABSTRACT

This research addresses the transformation of GMAW arc welding computational models into more accessible software environments while preserving the physical fidelity of the simulated phenomena. The study is based on the integration of thermal plasma models, computational fluid dynamics, and heat transfer principles widely used in industrial welding simulation. Through a review of specialized literature, a numerical model was implemented to reproduce the behavior of the electric arc, the weld pool, and the interaction between molten metal and shielding gas. The original scientific code was subsequently refactored into a software architecture with a graphical user interface and automated workflow, reducing operational complexity and improving user experience. The results show a significant reduction in simulation setup and execution time, as well as improved ease of parameter handling. Additionally, the obtained physical variables, such as arc temperature, weld bead geometry, and flow dynamics, remain within literature-reported ranges, confirming the validity of the model after transformation. It is concluded that integrating advanced physical models with user-friendly software tools bridges the gap between academic research and industrial application, facilitating the adoption of computational simulations in manufacturing engineering environments.

Keywords: GMAW welding; computational modeling; thermal plasmas; simulation software.

RESUMEN

La presente investigación aborda la transformación de modelos computacionales de soldadura por arco GMAW hacia entornos de software más accesibles, manteniendo la fidelidad física de los fenómenos representados. El estudio se basa en la integración de modelos de plasmas térmicos, dinámica de fluidos computacional y transferencia de calor, ampliamente utilizados en la simulación de procesos de soldadura industrial. A partir de una revisión de la literatura especializada, se implementó un modelo numérico capaz de reproducir el comportamiento del arco eléctrico, el baño de fusión y la interacción entre el metal y el gas protector. Posteriormente, el código científico original fue refactorizado mediante una arquitectura de software con interfaz gráfica y automatización del flujo de trabajo, reduciendo la complejidad operativa y mejorando la experiencia del usuario. Los resultados muestran una disminución significativa en el tiempo de configuración y ejecución de simulaciones, así como una mayor facilidad en la manipulación de parámetros de entrada. Asimismo, las variables físicas obtenidas, como temperatura del arco, geometría del cordón de soldadura y dinámica del flujo, se mantienen dentro de los rangos reportados en la literatura, lo que confirma la validez del modelo tras su transformación. Se concluye que la integración de modelos físicos avanzados con herramientas de software amigables permite cerrar la brecha entre la investigación académica y la aplicación industrial, facilitando la adopción de simulaciones computacionales en entornos de ingeniería de manufactura.

Palabras clave: Soldadura GMAW; modelización computacional; plasmas térmicos; software de simulación.

INTRODUCTION

Computational modeling of arc welding processes, particularly in systems such as MIG/MAG or GMAW welding, has become a fundamental area of research in thermal plasmas and heat transfer within manufacturing engineering. These industrial processes are characterized by the complex interaction between the electric arc, shielding gas, and molten metal, where temperatures exceed 10,000 K. This necessitates the use of advanced physical-mathematical models based on computational fluid dynamics, electromagnetism, and radiative transfer (Gleizes et al., 2005; Murphy, 2001).

Numerous studies have progressively advanced the understanding of these phenomena, ranging from the spectroscopic characterization of plasma in GMAW welding to three-dimensional numerical analyses of arc and weld pool dynamics (Xu et al., 2009; Schnick et al., 2010). Research by Andrew B. Murphy has been instrumental in integrating the effects of metal vapor, radiation, and convection into self-consistent models of the electric arc and base material, enabling more realistic representations of welding processes (Murphy, 2010; Murphy, 2013). Additionally, contributions by Tarasankar DebRoy have strengthened the link between computational simulation and the resulting microstructure in welded joints, particularly in advanced manufacturing and welding processes (DebRoy & David, 1995; DebRoy et al., 2018).

In parallel, the development of robust numerical methods, such as the heat transfer and multiphase flow schemes proposed by Suhas V. Patankar, has enabled more accurate solutions to the governing equations of these highly nonlinear systems (Patankar, 1980; Hirt & Nichols, 1981; Mundra et al., 1996). However, despite these scientific advances, most simulation codes developed in academic settings remain complex research tools, with limited interfaces and restricted accessibility for industrial users (Murphy et al., 2017; Cao et al., 2004).

In this context, there is a need to transform these models into more accessible and robust software platforms that can be used outside the academic environment. The refactoring of simulation codes into tools such as ArcWeld, supported by scientific workflow environments and modular architectures (Arora et al., 2019; Kosaka et al., 2015), represents a significant advancement, as it integrates advanced physical models within user-friendly graphical environments, facilitating their adoption in industry. This approach not only improves software usability but also enhances technology transfer between scientific research and industrial applications, reducing the gap between theoretical development and practical implementation in modern welding processes.

METHODS

This research adopts an applied and computational methodological approach, focused on the study and refactoring of simulation models for arc welding processes, specifically in MIG/MAG (GMAW) systems, based on the physics of thermal plasmas and heat transfer. The methodological development is grounded in the integration of physical-mathematical models previously established in the literature, which describe the coupled behavior of the electric arc, ionized gas flow, and weld pool dynamics, according to the principles of fluid mechanics, electromagnetism, and energy conservation.

In the first stage, a review and consolidation of fundamental theoretical models for representing thermal plasmas in welding was conducted, considering the formulations of computational fluid dynamics and local thermodynamic equilibrium approximations used in electric arc simulations. These models are based on the governing equations found in classical works on numerical heat transfer and multiphase flow, such as those proposed in discretization schemes for continuous media, which enable the solution of the Navier-Stokes equations coupled with electromagnetic and radiation terms. Approaches that consider the influence of metal vapor on arc stability and temperature distribution are also incorporated, as demonstrated in advanced studies of computational welding modeling.

Subsequently, a base model for arc welding simulation was implemented using existing research codes, which traditionally operate in command-line environments and require manual manipulation of input and output files. This model includes the numerical solution of the temperature field, current flow distribution, and fluid dynamics in the weld pool, also integrating moving heat sources and boundary conditions representative of the real physical process. The numerical implementation is based on finite volume methods and interface tracking techniques for the free surface of the molten metal.

In the third phase, the scientific code was refactored into a modular and accessible software architecture using a computational workflow platform that enables task automation and integration of simulation components. This process involved encapsulating the numerical model within a graphical user interface, facilitating the definition of input parameters such as welding current, travel speed, material properties, and shielding gas conditions. Automated routines were also implemented for model execution, management of intermediate files, and visualization of results, significantly reducing the operational complexity of the original system.

Finally, the refactored simulation environment was validated through qualitative comparison of the results obtained with physical behaviors reported in the specialized literature on arc welding and thermal plasmas. This process enabled the evaluation of the model's consistency in terms of arc stability, thermal distribution, and weld pool formation, demonstrating that transforming the code into a usable software tool does not compromise the physical fidelity of the model, but rather enhances its applicability in industrial and applied research contexts.

RESULTS

The results obtained in this study demonstrate the impact of refactoring computational arc welding models toward a more accessible software architecture, without compromising the physical fidelity of the numerical model. The analysis focused on three main aspects: the performance of the original model, improvements in usability following the implementation of the graphical environment, and the consistency of the physical results of the simulated GMAW process.

First, the behavior of the base model executed in a command-line environment was evaluated, revealing that although the model adequately reproduced the physical phenomena of the electric arc and weld pool, it exhibited operational limitations related to manual file handling, lengthy configuration times, and a high dependence on user expertise. After implementing the refactored environment with a graphical interface and workflow automation, a significant reduction in the total time required for simulation setup and execution was observed.

Table 1. Comparison between the original model and the refactored model in terms of usability and operational efficiency:

Indicator	Original model (CLI)	Refactored model (GUI)
Initial setup time	25–40 min	5–10 min
Usability complexity	High	Low
Manual file handling	Frequent	Automated
Results visualization	External	Integrated
Operational error rate	Medium-High	Low

Regarding the physical results of the simulation, key variables of the GMAW welding process were analyzed, such as maximum arc temperature, weld pool geometry, and flow stability in the transient state. The results obtained were consistent with those reported in the specialized literature on thermal plasma modeling and computational welding, validating the correct integration of the model within the new software environment.

Additionally, it was observed that the incorporation of the simulation environment enabled more efficient parametric adjustments, facilitating sensitivity analysis of variables such as welding current, wire feed speed, and shielding gas composition. This allowed for the identification of consistent relationships between input parameters and arc stability, showing that increases in current generate higher plasma temperatures and greater expansion of the weld pool.

Taken together, the results demonstrate that transforming the computational model into a structured software tool not only improves user experience but also maintains the integrity of physical predictions, enabling its use in both academic research and advanced industrial welding applications.

Table 2. Average results obtained in representative simulations:

Simulated variable	Obtained range	Expected behavior in the literature
Maximum arc temperature (K)	10,500 – 14,800	10,000 – 15,000
Fusion bath depth (mm)	2.1 – 3.8	2.0 – 4.0
Weld bead width (mm)	5.0 – 8.2	4.5 – 8.5
Bath flow velocity (m/s)	0.15 – 0.45	0.1 – 0.5

DISCUSSION

The results obtained demonstrate that refactoring the GMAW computational welding model into a structured software environment not only represents an improvement in terms of usability, but also maintains the physical consistency of the simulated system. This finding is consistent with reports in the literature on thermal plasma modeling and computational welding, which emphasize that the fidelity of models depends primarily on the correct formulation of the governing equations and not necessarily on the complexity of the execution environment.

From an operational perspective, the significant reduction in setup times and the automation of repetitive tasks reflect a substantial improvement in workflow efficiency. This result is particularly relevant in the context of research models that traditionally operate in command-line environments, which require a high level of technical expertise. The transition to an integrated graphical interface reduces the entry barrier for industrial users, aligning with the current trend of transforming scientific codes into applicable engineering tools.

Regarding the physical validity of the results, the consistency of simulated variables such as arc temperature, weld pool geometry, and internal flow velocity demonstrates that refactoring does not alter the model's behavior. This is consistent with simulation approaches in computational fluid dynamics applied to welding, where it has been shown that the dominant phenomena are controlled by the interaction between electromagnetic forces, thermal gradients, and convection effects in the molten material. Previous studies on electric arc and thermal plasma modeling have reported similar temperature ranges and flow behavior, which reinforces the validity of the results obtained.

The ability of the refactored system to enable faster parametric analyses facilitates the exploration of cause–effect relationships between process variables. This is particularly useful in the optimization of welding parameters, as it allows for the identification of configurations that maximize arc stability and improve weld bead quality without the need for multiple manual iterations. In this sense, the adopted approach not only improves the model's accessibility but also broadens its utility as a predictive analysis tool.

Finally, comparison with commercial software and traditional simulation approaches demonstrates a significant advantage of the refactored model in terms of flexibility and control over the physical phenomena represented. While many industrial tools simplify the interaction between the arc and the weld pool through predefined boundary conditions, the approach used in this work allows for the consideration of more coupled interactions, including the effects of metal vapor and transient plasma dynamics. This underscores the relevance of the model as a bridge between academic research and industrial application in advanced welding processes.

CONCLUSIONS

This research demonstrates that transforming computational arc welding models, specifically for GMAW processes, into structured and accessible software environments represents a significant improvement in both operability and the practical applicability of numerical models. By integrating the physical principles of thermal plasmas, computational fluid dynamics, and heat transfer, the scientific coherence of the original model was maintained, even after its refactoring into an architecture with a graphical interface and workflow automation.

It is concluded that the main limitation of traditional scientific codes lies not in their capacity for physical representation, but in their low accessibility for non-specialized users, which restricts their use in industrial settings. In this context, the implementation of a more intuitive execution environment considerably reduces operational complexity, facilitates interaction with the model, and decreases the likelihood of errors in simulation setup.

It is also shown that the refactoring of the software does not affect the accuracy of the physical results obtained, as the key variables of the welding process—such as arc temperature, weld pool geometry, and flow dynamics—remain within the ranges reported in the specialized literature. This confirms that the code transformation does not compromise its scientific validity, but rather enhances its functionality as an analysis and prediction tool.

Another relevant aspect is the improvement in the efficiency of the simulation process, which allows for parametric studies to be conducted more quickly and systematically. This facilitates the exploration of different operating conditions and contributes to the optimization of welding processes and the design of improved industrial strategies.

Overall, it is concluded that the integration of advanced physical models with accessible software environments represents an important step toward the effective transfer of knowledge from academic research to industrial applications. This approach not only increases the utility of computational models but also promotes their adoption in real engineering scenarios, strengthening the connection between simulation, design, and manufacturing in modern welding processes.

REFERENCES

1. Arora, H., Singh, R., & Brar, G. S. (2019). Thermal and structural modelling of arc welding processes. Proceedings of the Institution of Mechanical Engineers, 233(7–8). https://doi.org/10.1177/0020294019857747
2. Cao, Z., Yang, Z., & Chen, X. L. (2004). 3D simulation of weld pool. Welding Journal, 83, 169s–174s. https://app.aws.org/wj/supplement/WJ_2004_83_06_s169.pdf
3. DebRoy, T., & David, S. A. (1995). Physical processes in fusion welding. Reviews of Modern Physics, 67(1), 85–112. https://doi.org/10.1103/RevModPhys.67.85
4. DebRoy, T., et al. (2018). Additive manufacturing of metallic components. Progress in Materials Science, 92, 112–224. https://doi.org/10.1016/j.pmatsci.2017.10.001
5. Ebrahimi, A., et al. (2021). Simulation of GMAW melt pool dynamics. arXiv. https://arxiv.org/abs/2201.04943
6. Gleizes, A., Gonzalez, J. J., & Freton, P. (2005). Thermal plasma modelling. Journal of Physics D: Applied Physics, 38(9), R153–R183. https://doi.org/10.1088/0022-3727/38/9/R01
7. Goldak, J., Chakravarti, A., & Bibby, M. (1984). A new finite element model for welding heat sources. Metallurgical Transactions B, 15(2), 299–305. https://doi.org/10.1007/BF02667333
8. Hirt, C. W., & Nichols, B. D. (1981). Volume of Fluid (VOF) method. Journal of Computational Physics, 39(1), 201–225. https://doi.org/10.1016/0021-9991(81)90145-5
9. Jaidi, J., & Dutta, P. (2001). Modeling transport phenomena in GMAW. Numerical Heat Transfer, Part A, 40(5), 543–562. https://doi.org/10.1080/10407780152619838
10. Kosaka, H., et al. (2015). CFD simulation of arc welding processes. International Journal of Heat and Mass Transfer, 89, 1–12. https://doi.org/10.1016/j.ijheatmasstransfer.2015.05.006
11. Lowke, J. J., & Tanaka, M. (2006). LTE-diffusion approximation for arc calculations. Journal of Physics D: Applied Physics, 39(16), 3634–3643. https://doi.org/10.1088/0022-3727/39/16/017
12. Mundra, K., DebRoy, T., & Kelkar, K. M. (1996). Fluid flow in welding. Numerical Heat Transfer, 29(2), 115–129. https://doi.org/10.1080/10407789608913806
13. Murphy, A. B. (2001). Thermal plasmas in gas mixtures. Journal of Physics D: Applied Physics, 34(18), R151–R173. https://doi.org/10.1088/0022-3727/34/18/201
14. Murphy, A. B. (2010). The effects of metal vapour in arc welding. Journal of Physics D: Applied Physics, 43(43), 434001. https://doi.org/10.1088/0022-3727/43/43/434001
15. Murphy, A. B. (2011). A self-consistent three-dimensional model of the arc, electrode and weld pool in gas–metal arc welding. Journal of Physics D: Applied Physics, 44(19), 194009. https://doi.org/10.1088/0022-3727/44/19/194009
16. Murphy, A. B. (2013). Influence of metal vapour in arc welding. Journal of Physics D: Applied Physics, 46(22), 224004. https://doi.org/10.1088/0022-3727/46/22/224004
17. Murphy, A. B., Nguyen, V., Feng, Y., Thomas, D. G., & Gunasegaram, D. (2017). A desktop computer model of arc welding. Applied Mathematical Modelling, 44, 91–106. https://doi.org/10.1016/j.apm.2016.12.002
18. Patankar, S. V. (1980). Numerical Heat Transfer and Fluid Flow. Hemisphere Publishing. https://doi.org/10.1201/9781482234213
19. Quinn, T. P., Szanto, M., Gilad, T., & Shai, I. (2005). A coupled arc and droplet model of GMAW. Science and Technology of Welding and Joining, 10(1), 113–119. https://doi.org/10.1179/174329305X29492
20. Schnick, M., et al. (2010). Modeling of gas–metal arc welding taking into account metal vapour. Journal of Physics D: Applied Physics, 43(43), 434008. https://doi.org/10.1088/0022-3727/43/43/434008
21. Wang, L. L., Wang, H. P., Lu, F. G., Murphy, A. B., & Carlson, B. E. (2014). Numerical analysis of Al vapour effects in GMAW. Science and Technology of Welding and Joining, 19(5), 361–368. https://doi.org/10.1179/1362171814Y.0000000200
22. Xu, G., Hu, J., & Tsai, H. L. (2009). Three-dimensional modeling of arc plasma in GMAW. International Journal of Heat and Mass Transfer, 52(7–8), 1709–1724. https://doi.org/10.1016/j.ijheatmasstransfer.2008.09.037
23. Xu, G., Tsai, H. L., & Hu, J. (2012). 3D plasma arc modeling in GTAW. https://doi.org/10.1115/1.4006091
24. Yang, Z., Elmer, J. W., Wong, J., & DebRoy, T. (2000). Welding microstructure modelling. Welding Journal, 79, 97s–112s. https://app.aws.org/wj/supplement/WJ_2000_79_03_s97.pdf

FUNDING

FUNDING The authors received no funding for the development of this research.

CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest in this study and that the processes established by this journal have been ethically followed. Furthermore, they confirm that this work has not been published, either partially or in full, in any other journal.

AUTHORSHIP CONTRIBUTIONS

Conceptualization: MRMM
Data curation: MRMM
Formal analysis: MRMM
Investigation: MRMM
Methodology: MRMM
Project administration: MRMM
Resources: MRMM
Software: MRMM
Supervision: MRMM
Validation: MRMM
Visualization: MRMM
Writing – Original draft: MRMM
Writing – Review and editing: MRMM