https://www.periodicos.unis.edu.br/mythos/

INFLUENCE OF GMAW OPERATING PARAMETERS ON THE METALLURGICAL PROPERTIES OF AISI 304 STEEL WELDS

INFLUÊNCIA DOS PARÂMETROS OPERACIONAIS DO PROCESSO GMAW NAS PROPRIEDADES METALÚRGICAS DE SOLDAS EM AÇO AISI 304

Eduardo Pereira da Silva[1*], Allan Barbosa da Silva[2], Carlos Alberto Carvalho Castro[3]

[1] *PhD in Mechanical Engineering (UNIFEI). Federal Center for Technological Education of Minas Gerais – CEFETMG, Varginha, Brazil. edueps@yahoo.com.br*

[2] *M.Sc. in Mechanical Engineering (UNIFEI). Federal University of Itajubá - UNIFEI, Itajubá, Brazil. allansilva.vga@gmail.com*

[3] *PhD in Mechanical Engineering (UFMG). Federal Center for Technological Education of Minas Gerais – CEFETMG, Varginha, Brazil. carloscastro@cefetmg.br*

Editorial Details
Double-blind review system
Memory of a Scientific Event
23rd ABCM International Congress of Mechanical Engineering

Article History:
Received: September 05, 2025
Revised: October 2, 2025
Accepted: November 17, 2025
Published online: November 19, 2025

Editor-in-Chief:
Rodrigo Franklin Frogeri
Guest Editors:
Pedro dos Santos Portugal Júnior
Fabrício Pelloso Piurcosky
Technical Editor:
Eufrásia de Souza Melo

Funding:
This study received no external funding.

How to cite this article:
Silva, E. P. da., Silva, A. B. da, Castro, C. A. C. (2025). Influence of GMAW Operating Parameters on the Metallurgical Properties of AISI 304 Steel Welds. **Mythos**, v. 17, 2, 347-358. https://doi.org/10.36674/mythos.v17i2.1032

***Corresponding Author:**
Eduardo Pereira da Silva
edueps@yahoo.com.br

Abstract

This study investigates the influence of Gas Metal Arc Welding (GMAW) parameters, current, voltage, and travel speed, on the penetration and quality of welds in AISI 304 stainless steel. A full factorial Design of Experiments (DoE) was employed to assess both the individual and interactive effects of these parameters. The results demonstrated that welding current is directly proportional to penetration, whereas travel speed exhibits an inverse relationship, reflecting their combined control over heat input. Voltage, in turn, presented a non-linear effect, with a marked increase in penetration observed specifically at 25 V. The interaction plots further revealed that the combination of high current and low travel speed maximizes penetration, corroborating fundamental arc welding principles. Moreover, a synergistic effect was identified between intermediate current levels (116–120 A) and a voltage of 25 V, which substantially enhanced penetration. These findings highlight that weld bead geometry and metallurgical properties are direct consequences of the thermal cycle imposed by the selected process parameters. Consequently, effective optimization requires an integrated approach that considers not only the isolated effects but also the interactions among current, voltage, and travel speed, thereby ensuring the geometrical control, metallurgical integrity, and overall performance of the welded joint.

Keywords: Welding. GMAW. Sensitization. Stainless Steel. Austenitic.

Resumo

Este estudo investiga a influência dos parâmetros da Soldagem a Arco com Gás de Proteção (GMAW), corrente, tensão e velocidade de soldagem, sobre a penetração e a qualidade dos cordões em aço inoxidável AISI 304. Foi empregado um planejamento fatorial completo (DoE) para avaliar tanto os efeitos individuais quanto as interações desses parâmetros. Os resultados demonstraram que a corrente de soldagem é diretamente proporcional à penetração, enquanto a velocidade apresenta relação inversa, refletindo o controle combinado sobre o aporte térmico. A tensão, por sua vez, apresentou um efeito não linear, com um aumento significativo da penetração observado especificamente a 25 V. Os gráficos de interação revelaram ainda que a combinação de alta corrente com baixa velocidade maximiza a penetração, corroborando princípios fundamentais da soldagem a arco. Além disso, foi identificado um efeito sinérgico entre correntes intermediárias (116–120 A) e tensão de 25 V, que aumentou substancialmente a penetração. Esses fenômenos evidenciam que a geometria do cordão e as propriedades metalúrgicas da solda são consequências diretas do ciclo térmico imposto pelos parâmetros de processo selecionados. Portanto, a otimização eficaz requer uma abordagem integrada que considere não apenas os efeitos isolados, mas também as interações entre corrente, tensão e velocidade de soldagem, assegurando, assim, o controle geométrico, a integridade metalúrgica e o desempenho global da junta soldada.

Palavras-chave*: Soldagem. GMAW. Sensitização. Aço inoxidável. Austenítico.*

Declaration on the Use of Artificial Intelligence to prepare the manuscript

The authors declare that artificial intelligence (AI) tools were used during the preparation of the manuscript submitted to Mythos. The platform used was ChatGPT (version GPT-4.5), developed by OpenAI. The tool was employed between April 15 and April 16, 2025, specifically for tasks such as text editing, language enhancement, and translation between Portuguese and English.

Data available

The research data have not been made available by the authors in a public repository.

1 INTRODUCTION

The soldering process, particularly arc welding, represents one of the most critical and widely utilized manufacturing technologies across modern industrial sectors. Its significance stems from its ability to provide strong, durable, and reliable joints in metallic structures, making it indispensable in fields such as energy, transportation, and construction. According to recent studies, welding continues to evolve as a cornerstone of advanced manufacturing, with increasing emphasis on automation, precision, and sustainability (Zhang et al., 2023).

Among the various industries relying heavily on welding, the petrochemical and shipbuilding sectors stand out due to their stringent safety and performance requirements. These industries are experiencing renewed growth driven by deep-sea oil and gas exploration, offshore wind infrastructure, and liquefied natural gas (LNG) carrier development. The structural integrity of pipelines, pressure vessels, and hull components is directly tied to the quality of welded joints, where any defect can lead to catastrophic failures *(Li & Wang, 2022)*.

Welding, like many industrial processes, has undergone significant technological advancement, yet it remains highly sensitive to process variables and environmental conditions. This sensitivity necessitates comprehensive research and systematic evaluation of welding techniques to ensure repeatability, reliability, and compliance with international standards such as ISO 3834 and ASME Section IX. Despite decades of development, welding still presents challenges related to residual stresses, distortion, and microstructural heterogeneity, which can compromise long-term performance (da Silva et al., 2025; Kou et al., 2021).

Gas Metal Arc Welding (GMAW), also known as MIG (Metal Inert Gas) welding, has emerged as one of the most versatile and efficient welding processes available today. Its widespread adoption is attributed to several key advantages, including high deposition rates, minimal post-weld cleaning, and the ability to operate in all welding positions. As highlighted by Costa et al., (2020) and Chen et al. (2022), GMAW offers superior productivity compared to traditional Shielded Metal Arc Welding (SMAW) and Tungsten Inert Gas (TIG) methods, particularly in automated and robotic systems. This makes it ideal for high-volume production and large-scale structural fabrication.

One of the defining features of GMAW is its adaptability to a broad range of materials, including carbon steels, stainless steels, aluminum alloys, and nickel-based superalloys. This versatility is further enhanced by the availability of various shielding gas mixtures, which play a crucial role in arc stability, weld bead geometry, and metallurgical properties. Common inert shielding gases include argon (Ar), helium (He), and blends with reactive gases such as carbon dioxide (CO_2) or oxygen (O_2). Park et al. (2023)confirms that the selection of shielding gas significantly influences the heat transfer dynamics and metal transfer modes during welding.

The shielding gas not only protects the molten weld pool from atmospheric contamination, preventing oxidation and porosity, but also affects arc characteristics such as voltage drop, current density, and droplet formation. For instance, higher argon content typically results in a more stable arc and smoother metal transfer, while CO_2 addition increases penetration but may lead to spatter (Cui et al., 2024).

The GMAW process is governed by a complex interplay of multiple interdependent variables, each of which must be carefully controlled to achieve consistent weld quality. Key parameters include welding current, arc voltage, electrode feed speed, travel speed, electrode extension (stick-out), shielding gas flow rate, and joint geometry. As noted by Khrais et al. (2024) and Ribeiro et al., (2025) and as corroborated in contemporary research, even minor fluctuations in these parameters can lead to significant variations in weld bead profile, penetration depth, and fusion zone microstructure (Martín et al., 2022).

The interaction between welding parameters and material response is particularly critical when working with austenitic stainless steels such as AISI 304. This grade is widely used in corrosive environments due to its excellent resistance to oxidation and chloride-induced stress corrosion cracking. However, its performance is highly dependent on the thermal history experienced during welding. The improper heat input, dictated by current, voltage, and travel speed, can promote sensitization, delta ferrite formation, and intergranular corrosion susceptibility (Zhao et al., 2023). Thus, controlling thermal cycles is essential to preserve the material's functional integrity.

Microstructural evolution in the weld zone is directly influenced by the cooling rate, which in turn is determined by welding speed and heat input. Rapid cooling can lead to fine-grained structures with improved strength but may increase residual stresses and cracking risk. Conversely, slow cooling may result in coarse grains and undesirable phase transformations. (Silva et al., 2015) and Kim et al. (2022) reveals that in AISI 304, excessive heat input promotes the formation of secondary phases such as chi (χ) and sigma (σ), which embrittle the weld metal and reduce toughness. Hence, optimizing welding speed is crucial to balance mechanical properties and microstructural stability.

Moreover, the chemical composition of the filler metal and base material plays a synergistic role in determining the final weld properties. In dissimilar metal welding or when using non-matching consumables, compositional gradients can develop across the fusion zone, leading to localized weaknesses (Santos et al., 2023). In addition to metallurgical concerns, mechanical performance—including tensile strength, ductility, impact toughness, and fatigue resistance—must be evaluated to ensure structural reliability. Recent research indicates that welds in AISI 304 stainless steel often exhibit reduced toughness in the heat-affected zone (HAZ) due to grain coarsening and phase instability (Nguyen et al., 2022). Therefore, optimizing current and voltage settings to minimize HAZ width and maintain favorable phase balance is a key objective in process development.

Despite these technological advances, human expertise remains indispensable in interpreting results, validating models, and ensuring compliance with safety standards. The complexity of welding phenomena, spanning thermodynamics, fluid dynamics, solid-state transformations, and electrochemistry, requires multidisciplinary knowledge.

The GMAW process, while mature, continues to be a dynamic field of research and innovation particularly when applied to special alloys. The pursuit of higher quality, efficiency, and sustainability drives ongoing investigation into the effects of welding parameters on microstructure and performance of the joints, particularly in critical materials like AISI 304 stainless steel. Thus, this paper aims at an assessment of the influence of the main operating parameters of GMAW process, such as current, voltage and welding speed on the microstructure formed in AISI 304 steel.

2 MATERIALS AND METHODS

For the tests we used the wire (electrode) solid AWS ER-308Lsi with 1.0 mm diameters, and Argon gas to protect the weld pool. The wire composition is presented in Table 1.

Table 1

Chemical composition of electrode AWS ER-308Lsi.

C	Mn	P	Si	Cr	Ni	Mo
0.023	1.55	-	0.75	20.0	10.1	0.17

Source: http://www.esab.com.br

The specimens were prepared from AISI 304 stainless steel with dimensions of 65 × 150 × 6.35 mm. The chemical composition of the material is presented in Table 2.

Table 2

Chemical composition of stainless steel AISI 304.

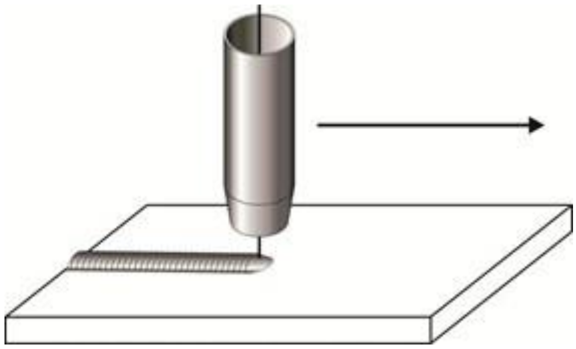
C	Mn	P	Si	Cr	Ni	S
0.8	2.00	0.045	1.00	18.0 – 20.0	8.0 – 10.5	0.030

Source: http://www.eutetic.com/catalogoinox_parte1.indd

The welds were carried out using the bead-on-plate (BOP) technique along the longitudinal axis of the specimens, with the welding torch maintained perpendicular to the surface, as illustrated in Figure 1.

Figure 1

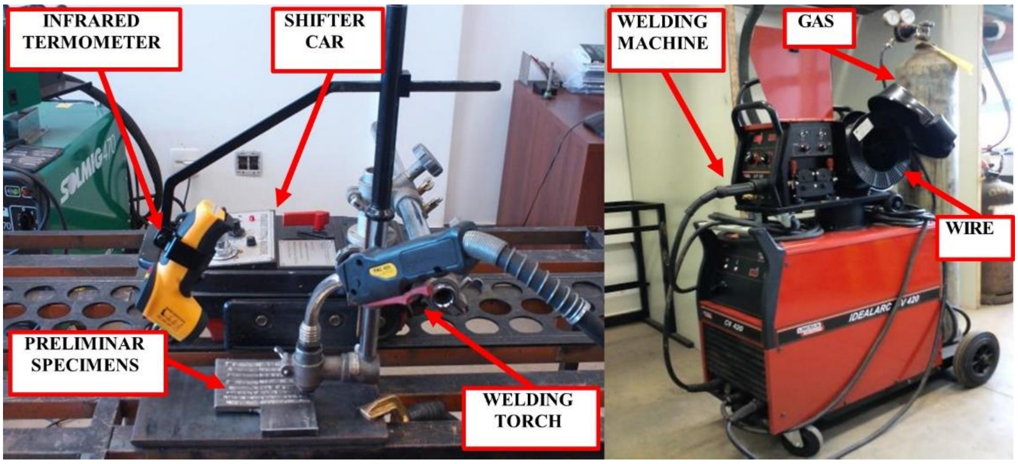
Bead-on-plate welding configuration.



To meet the objectives of this study, a test bench was assembled comprising a mechanized torch displacement system (SB1-30, *Soldas Brazil*) and welding equipment (Idealarc CV-420, Lincoln Electric), with control of current, voltage, and other relevant variables (Figure 2).

Figure 2

Testing bench.



The experimental design (DoE) was generated using Minitab software, employing a full factorial design with three factors at three levels each, resulting in a 3^3 design. The current and voltage levels were selected based on preliminary trials conducted in accordance with the wire manufacturer's recommendations, which specify voltage values between 15 V and 32 V and current values between 100 A and 225 A. From these preliminary tests, the current and voltage settings that produced weld beads with the most favorable geometric characteristics were identified and subsequently adjusted slightly above and below within the acceptable range, as presented in Table 3.

Table 3

Factors and levels to be varied.

Variable	Level 1	Level 2	Level 3
Current (Ampere)	111	116	120
Voltage (Volt)	22	24	25
Speed (mm/min.)	325	390	465

3 RESULTS AND DISCUSSION

All weld beads exhibited a short-circuit metal transfer mode. The Design of Experiments (DoE) resulted in Table 4, which presents the three factors and their respective variation levels, corresponding to the equipment settings applied in the tests. The penetration values shown in the results column were determined through macrographic analysis of the welded specimens (Figure 3) and subsequently included for data analysis.

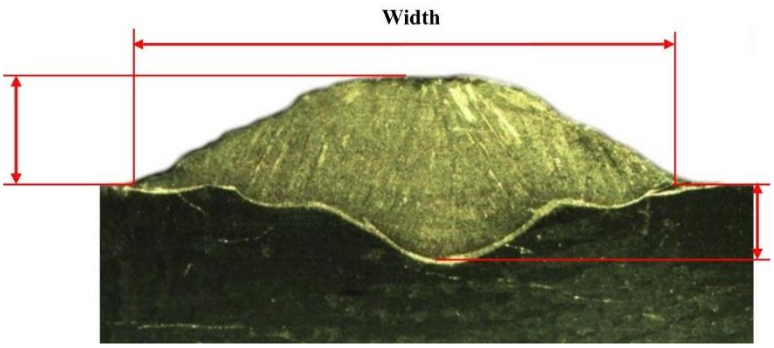
Table 4

Design of Experiments

Specimen's execution order	Input Variable			Results	Specimen's execution order	Input Variable			Results
	Speed (mm/min.)	Current (A)	Voltage (V)	Depth (mm)		Speed (mm/min.)	Current (A)	Voltage (V)	Depth (mm)
01	325	111	22	0.59	15	390	116	25	0.82
02	325	111	24	0.41	16	390	120	22	0.98
03	325	111	25	0.75	17	390	120	24	0.49
04	325	116	22	0.95	18	390	120	25	1.00
05	325	116	24	0.64	19	465	111	22	0.56
06	325	116	25	1.34	20	465	111	24	0.85
07	325	120	22	1.24	21	465	111	25	0.72
08	325	120	24	0.98	22	465	116	22	0.61
09	325	120	25	0.76	23	465	116	24	0.46
10	390	111	22	0.74	24	465	116	25	1.26
11	390	111	24	0.82	25	465	120	22	0.61
12	390	111	25	1.00	26	465	120	24	0.36
13	390	116	22	0.48	27	465	120	25	0.88
14	390	116	24	0.52	-	-	-	-	-

Figure 3

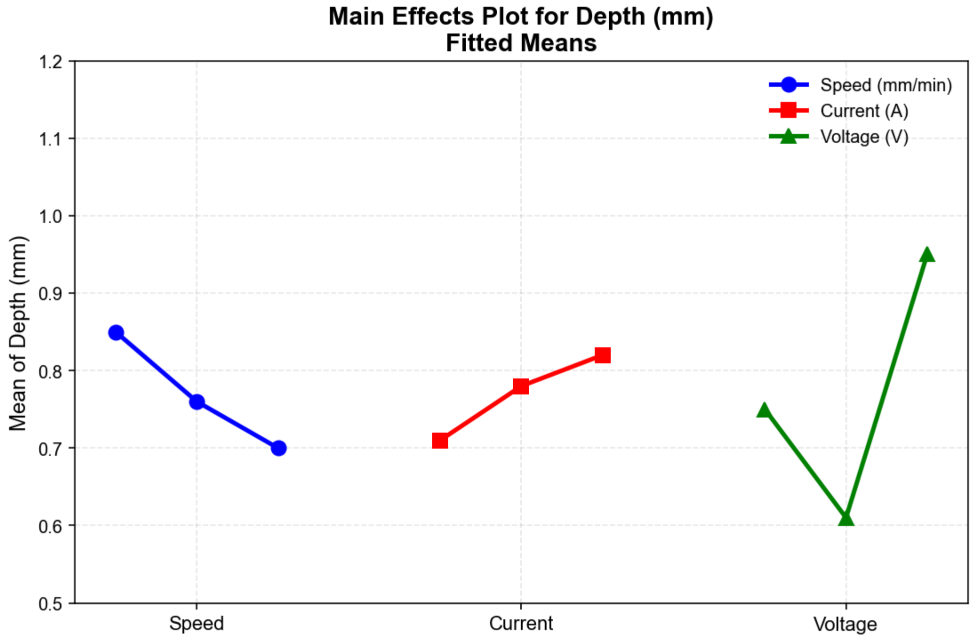
Macrography Specimen 06 with 10X magnification.



The data generated from the DoE were analyzed to determine the influence of each parameter on weld bead penetration, as well as the effects of their interactions. The outcomes of this analysis are presented in Figures 4 and 5.

Figure 4

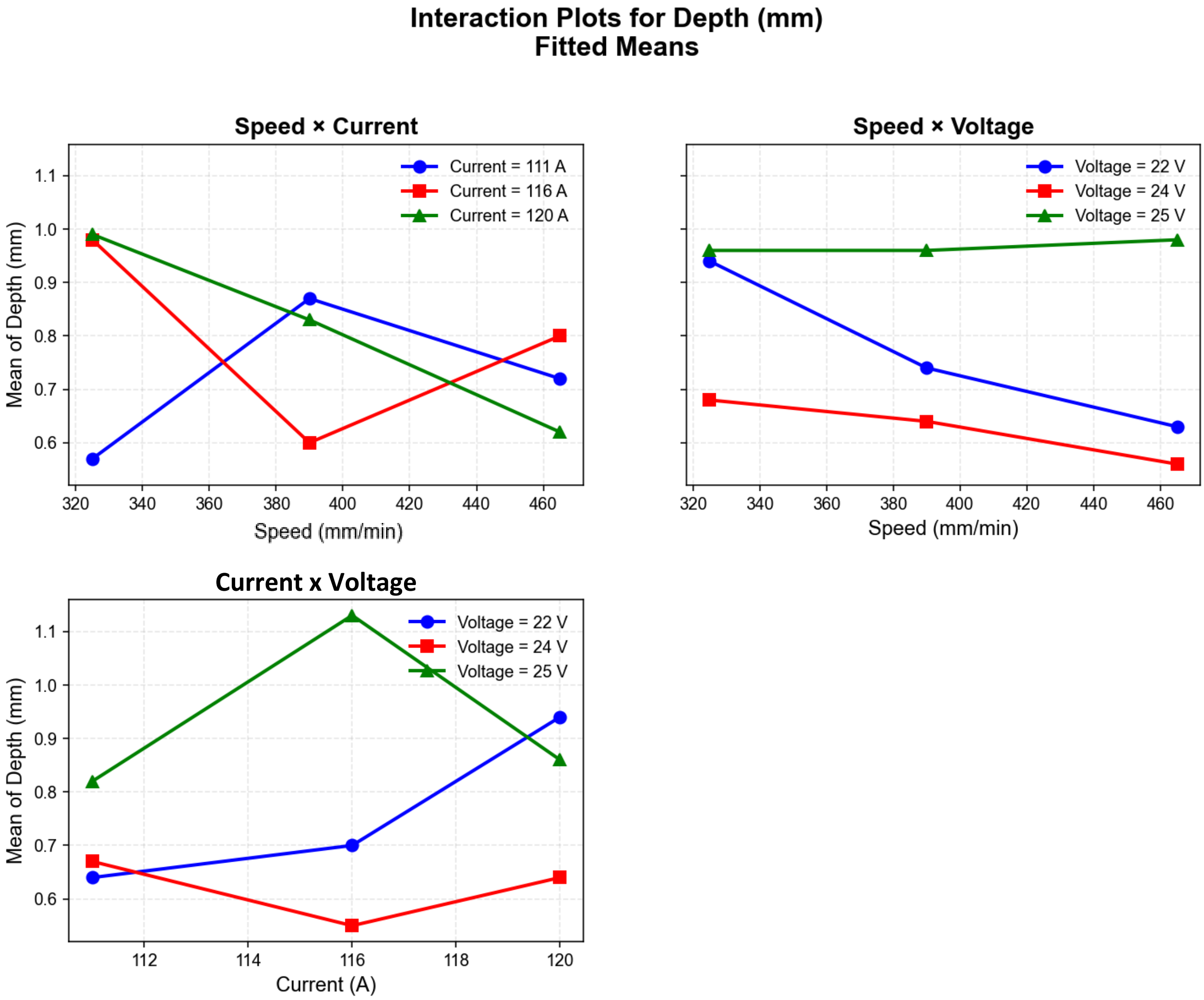
Effects of the main parameters on penetration.



The analysis of the main effects plot in the Figure 4, indicates that welding speed exerts an inversely proportional influence on penetration. As the speed increases from 325 to 465 mm/min, the penetration depth decreases continuously. This behavior is attributed to the reduced thermal interaction time between the electric arc and the base metal, resulting in lower heat input per unit length of the weld. In contrast, welding current shows a directly proportional relationship, producing a consistent increase in penetration within the range of 111 to 120 A. This finding corroborates its significance in the process, as current is directly associated with the amount of heat generated in the arc. Voltage, however, exhibits a distinct and non-linear behavior: while the variation from 22 V to 24 V leads to a reduction in penetration, at 25 V a significant increase is observed, reaching the highest mean value among the conditions examined.

Figure 5

Interaction of the main parameters on penetration.



The interaction plots in Figure 5 complement this analysis by elucidating the combined effects of the parameters. The interaction between speed and current demonstrates that, at higher current levels, reducing the welding speed enhances heat input, thereby increasing penetration. At lower current levels, however, the influence of speed is less pronounced. The interaction between speed and voltage shows that the 25 V condition is more sensitive to speed variations, maintaining higher penetration at lower speeds, whereas lower voltages (22–24 V) result in more uniform yet consistently decreasing responses. Finally, the interaction between current and voltage reveals that, at intermediate current levels (116–120 A), the application of 25 V produces a substantial increase in penetration, suggesting a synergistic effect between these parameters.

In summary, the results indicate that welding current and speed are the most decisive factors governing penetration, while voltage exerts a secondary influence, albeit with a non-linear behavior and significant interactions. The combination of high current with reduced welding speed maximizes heat input, which is consistent with fundamental principles of arc welding. Furthermore, the application of 25 V at intermediate current levels was shown to maximize penetration, underscoring the importance of an integrated analysis of process parameters to achieve effective control of bead geometry and metallurgical quality of the welded joint.

LIMITATIONS AND FUTURE RESEARCH

Research in the field of welding, in its general context, faces intrinsic limitations stemming from the complex and multivariable nature of its processes. The dynamic interaction between thermo-electrical parameters, metallurgical phenomena, and operational conditions creates systems that are difficult to fully characterize. Additionally, the frequent need to conduct studies at laboratory scale, under controlled conditions, may limit the direct transferability of results to industrial scenarios, where factors such as complex geometries and restraint stresses significantly influence the final outcome.

To overcome these limitations, future research perspectives should prioritize the integration of experimental data, advanced numerical modeling, and artificial intelligence techniques to develop robust predictive tools. The systematic validation of optimized parameters in large-scale prototypes is essential to consolidate data reliability. Furthermore, the exploration of hybrid processes and the development of in-situ sensing systems for real-time control represent promising frontiers to transcend current constraints and advance the control, efficiency, and reliability of critical alloy welding.

CONCLUSION

This study has elucidated the decisive influence of GMAW welding parameters on the geometrical and metallurgical properties of the weld bead. The results demonstrate that welding current and travel speed emerge as the primary control variables, directly governing heat input and, consequently, penetration, a critical geometrical feature for the mechanical strength of the joint.

The welding current, being intrinsically related to the arc heat intensity, was shown to be directly proportional to penetration, whereas an increase in welding speed reduced thermal interaction and thus produced a shallower weld. Voltage, although exerting a secondary effect, revealed a non-linear and synergistic behavior, particularly at its highest level (25 V), where it significantly enhanced penetration when combined with intermediate current levels.

These complex parametric interactions underline that the final metallurgical quality of the joint, including microstructure, residual stresses, and susceptibility to defects, is a direct consequence of the thermal cycle imposed by the specific combination of parameters. Therefore, process optimization critically depends on an integrated analysis that considers not only the individual effects but, above all, the interactions between current, speed, and voltage.

The identified combination of high current and low speed maximizes heat input, aligning with the fundamental principles of arc welding, while the synergy under specific conditions (e.g., 25 V and currents of 116–120 A) provides a pathway to simultaneously optimize bead geometry and control metallurgical properties, thereby ensuring the integrity and performance of the welded joint.

REFERENCES

Chen, L., Zhao, R., & Huang, Y. (2022). Comparative study of GMAW and SMAW in automated manufacturing systems. *The International Journal of Advanced Manufacturing Technology*, *120*(5–6), 3021–3035. https://doi.org/10.1007/s00170-022-08867-2

Costa, A. L. G., Magalhães, R. R., Silva, E. P., Castro, C. A. C., & Rabelo, G. F. (2020). Technical feasibility of hard coating by flux-cored arc welding on a sugarcane cutting knife. *The International Journal of Advanced Manufacturing Technology*, *111*, 999–1013.

da Silva, E. P., Castro, C. A. C., & Correa, E. O. (2025). Joining of Ti6Al4V/Al7075-T6 alloys without forming an intermediate layer by the GMAW process. *The International Journal of Advanced Manufacturing Technology*, *136*(11–12), 5083–5102. https://doi.org/10.1007/s00170-025-15131-8

Silva, E. P. da, Silva, A. B. da, Lima, E. W. de, Castro, C. A. C., & Lopes, A. de O. (2015, December 6). The influence of the operating parameters of the GMAW process in the metallurgical properties of the welded region of stainless steel AISI 304. *23rd ABCM International Congress of Mechanical Engineering*. https://doi.org/10.20906/CPS/COB-2015-0853

Khrais, S., Mohammed, A., Al, A., & Darabseh, T. (2024). Effect of TIG welding parameters on 316 L stainless steel joints using taguchi L27 approach. Materials Research Express, 11. https://doi.org/10.1088/2053-1591/ad1cab

Kim, S., Park, N., & Lee, Y. (2022). Formation and embrittlement effects of sigma phase in austenitic stainless steel welds. *Acta Materialia*, *224*, 117521. https://doi.org/10.1016/j.actamat.2021.117521

Kou, S., Chen, M., & Ahmed, T. (2021). Welding process challenges in modern industry: A review of defects, distortions, and control strategies. *Welding in the World*, *65*(8), 1457–1473. https://doi.org/10.1007/s40194-021-01123-7

Li, X., & Wang, J. (2022). Structural integrity of welded joints in offshore engineering: Challenges and solutions. *Ocean Engineering*, *261*, 112045. https://doi.org/10.1016/j.oceaneng.2022.112045

Cui, X., Chen, J., Chen, M., & Wu, C. (2024). Investigating arc and molten metal transport phenomena in gas metal arc welding with Ar–CO2 gas mixtures using a numerical method. Physics of Fluids. https://doi.org/10.1063/5.0194395.

Martín, O., López, F., & Ríos, J. (2022). Real-time monitoring of GMAW parameters using sensor fusion and machine learning. *Science and Technology of Welding and Joining*, *27*(3), 210–225. https://doi.org/10.1080/13621718.2021.2012345

Nguyen, V., Tran, H., & Le, Q. (2022). HAZ toughness degradation in austenitic stainless steel welds: Mechanisms and mitigation. *Engineering Fracture Mechanics*, *275*, 108876. https://doi.org/10.1016/j.engfracmech.2022.108876

Park, J., Kim, D., & Lee, C. (2023). Influence of shielding gas composition on arc stability and metal transfer in GMAW of stainless steels. *Materials Science and Engineering: A*, *864*, 144567. https://doi.org/10.1016/j.msea.2023.144567

Ribeiro, D. A., Castro, C. A. C., da Silva, E. P., & Correa, E. O. (2025). Influence of the applied mechanical vibration on the porosity level, microstructure and hardness of the AA-7075-T6 alloy weldments using GMAW-STT process. *The International Journal of Advanced Manufacturing Technology*, *139*(7–8), 3675–3692. https://doi.org/10.1007/s00170-025-16103-8

Santos, T., Noronha, M., & Silva, C. (2023). Microsegregation and phase distribution in GMAW welds of AISI 304 using EBSD and EDS analysis. *Metallurgical and Materials Transactions A*, *54*(2), 678–692. https://doi.org/10.1007/s11661-022-06890-3

Zhang, Y., Liu, S., & Wang, H. (2023). Recent advances in arc welding technologies for sustainable manufacturing. *Materials & Design*, *225*, 111234. https://doi.org/10.1016/j.matdes.2022.111234

Zhao, H., Sun, D., & Yang, M. (2023). Thermal history and sensitization behavior in AISI 304 stainless steel welds. *Corrosion Science*, *210*, 110890. https://doi.org/10.1016/j.corsci.2022.110890