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Ruslan Kulykovskyi — Candidate of Technical Sciences, Associate Professor, Vice-Rector for Scientific and Pedagogical Work and Issues of University Development Prospects, National University Zaporizhzhia Polytechnic, Zaporizhzhia, Ukraine, *e-mail: kulikovski@zp.edu.ua*, ORCID: 0000-0001-8781-2113

Kyrylo Krasnoselsky — Postgraduate student of the Department of Integrated Welding Technologies and Structural Modeling, National University Zaporizhzhia Polytechnic, Zaporizhzhia, Ukraine, *e-mail: kvkras@gmail.com*, ORCID: 0009-0006-5251-9076

MODELING OF THE INFLUENCE OF SHIELDING GAS COMPOSITION ON THE GEOMETRY OF THE DEPOSITED LAYER IN WIRE ARC ADDITIVE MANUFACTURING (WAAM)

Purpose. *To develop a generalized theoretical approach for describing the influence of shielding gas composition on the geometry of the deposited layer in the WAAM process, taking into account arc thermophysics, surface phenomena, and the thermohydrodynamics of the weld pool.*

Research methods. *Methods of analysis and generalization of scientific publications, the principles of heat transfer theory and fluid mechanics with a free surface, physical modeling of thermocapillary convection, as well as a semi-empirical mathematical description based on the introduction of integral gas-environment indices.*

Results. *A cause-and-effect framework describing the influence of shielding gas composition on effective heat input, melt surface activity, and the geometric parameters of the deposited layer was developed. A gas thermophysical index (GTI) was proposed to characterize the effect of the gas mixture on the thermal state of the arc, and a gas activity index (GAI) was introduced to reflect the influence of active components on the thermocapillary response of the molten pool. A structure of semi-empirical model was constructed, relating gas composition to bead width, layer height, and penetration depth.*

Sciettific novelty. *An integrated approach describing the influence of shielding gas on the formation of deposited-layer geometry in WAAM is proposed, in which the gas environment is considered as a physically meaningful process parameter. For the first time within the framework of this formulation, a system of integral indices, GTI and GAI, has been introduced for the formalized consideration of the thermophysical and chemical-surface channels through which gas mixture affects the process.*

Practical value. *The obtained results may serve as a theoretical basis for selecting shielding gas composition, predicting deposited-layer geometry, further calibration of the model using experimental data, and developing process control algorithms for WAAM.*

Key words: *Wire Arc Additive Manufacturing (WAAM), shielding gas, deposited layer, bead geometry, thermocapillary convection, weld pool, mathematical modeling, penetration depth.*

Introduction

Wire Arc Additive Manufacturing (WAAM) is considered one of the most promising directions in additive manufacturing of large-scale metallic components due to its high deposition productivity, efficient material utilization, and the possibility of employing conventional arc welding equipment integrated with robotic motion systems [1–4]. Particular interest in WAAM is driven by its suitability for producing complex-shaped parts in mechanical engineering, energy systems, transportation, and aerospace industries, where, in addition to productivity, geometric accuracy, stability of layer-by-layer deposition, and controllability of the thermal state of the process are of decisive importance [1–4].

One of the central scientific and technological challenges of WAAM is the formation of the deposited layer geometry. Bead width, layer height, and penetration depth directly influence the dimensional accuracy of the manufactured component, interlayer repeatability, accumulation of geometric deviations, surface waviness, and the extent of subsequent machining. In a multilayer process, even minor deviations in the geometry of an individual pass may lead to significant deterioration in the overall quality of the component. Therefore, the problem of predicting and controlling layer geometry parameters is among the key issues for the further development of WAAM as an industrial manufacturing technology [2–4].

Among the factors determining the geometry of the deposited layer, the composition of the shielding gas occupies a significant role. The gaseous environment affects not only the protection of molten metal from atmospheric contamination but also the thermal state of the arc, the mode

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of electrode metal transfer, and wetting and flow conditions within the molten pool [5–9]. Variations in the ratio of inert and active components in the gas mixture may alter the spatial distribution of the heat flux, the surface condition of the molten metal, and the intensity of thermocapillary convection. Consequently, these changes influence bead shape, penetration depth, and the stability of layer formation [5–9]. This represents a fundamental feature of WAAM: the composition of the shielding gas acts not merely as a technological condition of the process but also as a factor governing the morphology of the deposited material.

At the same time, the current state of research is characterized by a certain inconsistency. On one hand, numerous experimental studies convincingly demonstrate that variations in shielding gas composition significantly influence bead geometry and the quality of multilayer deposition [5–7]. On the other hand, in most existing WAAM models, the shielding gas is either considered only indirectly through process parameters or treated as an auxiliary experimental condition without being introduced into the analytical description of the process as an independent physically meaningful variable [2–4, 10, 11]. As a result, a discrepancy arises between the experimentally confirmed significance of the gaseous environment and its insufficient integration into theoretical models describing layer geometry formation.

Another gap lies in the fact that many existing approaches consider separately the thermophysical influence of the gas on the arc and the surface phenomena occurring within the molten pool. In reality, however, these mechanisms act simultaneously in the WAAM process and determine the final layer morphology as the result of the coupled interaction of heat transfer, fluid flow, and surface forces [8–11]. For this reason, empirical selection of gas mixtures alone is insufficient for effective control of deposition geometry. Instead, a generalized approach is required that would relate the composition of the shielding gas to effective heat input, the thermocapillary response of the molten pool, and the principal geometric parameters of the deposited layer.

In this context, the present work is aimed at developing a generalized theoretical description of the influence of shielding gas composition on the geometry of the deposited layer in WAAM. Within this framework, the gaseous environment is considered as a physically meaningful process parameter associated with arc thermophysics, the surface activity of the molten metal, and the thermo-hydrodynamic state of the weld pool.

Analysis of research and publications

The initial stage of research development in the field of WAAM was associated with the formation of a general understanding of this technology as a high-productivity type of wire-based additive manufacturing for metallic components. Fundamental review studies demonstrated that WAAM possesses significant advantages for large-scale parts due to high deposition rates, efficient material utilization, and the possibility of integrating standard arc welding power sources with robotic motion systems. At the same time, these studies clearly outlined the main limitations of the process, including insufficient geometric accuracy, surface waviness, instability of bead shape, the influence of thermal history, and the need for additional quality assurance measures [1–5]. Thus, at the initial stage, scientific attention was mainly focused on the general technological capabilities of WAAM and on the challenge of achieving stable product quality.

Further development of the research area was associated with the transition from a general technological description to the analysis of individual factors determining the morphology of the deposited layer. In this context, particular importance was given to studies devoted to the influence of process parameters, heat input, motion trajectory, interlayer temperature, and cooling conditions on bead width, layer height, and penetration depth. At this stage, deposition geometry began to be considered not merely as a geometric outcome of the process but as an integral indicator of heat and mass transfer, solidification kinetics, and the stability of multilayer buildup [2–5, 12, 13]. However, even in these studies, the composition of the shielding gas generally remained either a background condition or a variable recorded experimentally without further inclusion in a physically meaningful analytical description.

A separate and more application-oriented stage of research consists of studies directly addressing the influence of shielding gas in WAAM. For stainless steels, a methodology has been proposed for selecting multicomponent Ar-based gas mixtures taking into account the regularity of metal transfer, geometric characteristics, and metallurgical features of deposited walls [6]. For wire arc additive processes based on Ar-CO_2 mixtures, experimental studies have shown that changes in gas composition affect the thermal regime, the local morphology of the deposit, and the quality of building different geometries [7]. In large-scale additive manufacturing of martensitic 410 steel, it was established that the type of gas mixture influences not only microstructure and mechanical properties but also process stability, which is directly related to deposition morphology [8]. For aluminum thin-walled WAAM structures, the importance of additional shielding has been demonstrated, affecting the regularity of metal transfer, surface cleanliness, and geometric quality [9]. The body of these works indicates that shielding gas in WAAM can no longer be regarded as a secondary factor. However, most of these studies are predominantly experimental and are focused on specific materials, mixtures, and operating regimes.

The physical foundations of such influence were established earlier in classical studies of arc welding. The work of Pires, Quintino, and Miranda demonstrated that the composition of gas mixtures significantly affects arc stability, metal transfer modes, and the process characteristics of Gas Metal Arc Welding (GMAW) [10]. In the study by

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Lu, Fujii, and Nogi, it was shown that even small additions of O_2 or CO_2 to argon alter the oxygen content in the molten metal and may lead to a change in the character of Marangoni convection, thereby affecting weld pool shape and penetration depth [11]. A comprehensive analysis of the influence of various shielding gases on metal welding processes was presented in the work of Kah and Martikainen [14]. For WAAM applications, these studies are of fundamental importance, as they explain the mechanism of the gas environment not only through arc energetics but also through changes in the surface state of the molten metal and the restructuring of flow patterns within the weld pool. This marks the origin of the scientific direction linking gas composition with macroscopic layer geometry through the thermohydrodynamics of the molten pool.

The next important stage in the development of research is associated with numerical and analytical modeling of WAAM. In particular, Bai et al. developed a three-dimensional model of heat transfer and molten pool flow for multilayer PAW-based WAAM, demonstrating the decisive role of interlayer thermal history, melt pool hydrodynamics, and cooling conditions in the formation of the geometry of subsequent layers [12]. Oliveira, Santos, and Miranda summarized the fundamental welding concepts relevant to fusion-based additive manufacturing, including rapid thermal cycles, solidification, defect formation, and residual stress development [13]. However, even in advanced numerical approaches, the shielding gas is typically considered indirectly through the heat source model, process parameters, or experimentally specified conditions rather than being introduced into the model as an independent physically meaningful variable. Consequently, current models describe the thermal and hydrodynamic states of the process relatively well but still do not provide a generalized analytical relationship linking gas composition, arc conditions, surface phenomena, and layer geometry.

It is also important to highlight studies specifically evaluating the influence of shielding gas on the geometric quality of WAAM. The work of Gurčík, Kovanda, and Rohan directly focused on the effect of shielding gas on the geometrical quality of WAAM technology [15]. Together with the aforementioned WAAM studies, this confirms the relevance of the problem from the standpoint of layer geometry control rather than solely from the perspectives of metallurgy or mechanical properties. At the same time, comparison of these results shows that existing solutions are predominantly either purely experimental or technological-empirical in nature and do not provide a reduced physically interpretable model suitable for parametric prediction and further optimization of gas mixture composition.

Thus, a critical analysis of previous and contemporary publications allows several key stages to be identified:
- first, the establishment of WAAM as a high-productivity technology characterized by challenges related to geometric accuracy and stability [1–5];
- second, the accumulation of experimental data on the influence of specific gas mixtures on deposition morphology and material properties [6–9, 15];
- third, the development of fundamental concepts concerning the role of shielding gas through metal transfer modes, surface tension effects, and Marangoni convection [10, 11, 14];
- fourth, the development of thermohydrodynamic models of WAAM, in which the gas environment has not yet become a full-fledged parameter of a generalized description [12, 13]. This last circumstance defines the unresolved part of the overall problem.

The unresolved aspect of the problem is the absence of a generalized analytical approach in which the composition of the shielding gas would be incorporated into the process description as a parameter simultaneously characterizing its thermophysical influence on the thermal state of the arc and its chemical-surface influence on the thermocapillary response of the molten pool. This limitation prevents the transition from empirical selection of gas mixtures to physically grounded prediction of bead width, layer height, and penetration depth under WAAM conditions. Therefore, the role of the present work in addressing this problem lies in the development of a reduced theoretical approach in which the gaseous environment is parameterized through integral indices and linked to the geometry of the deposited layer through the thermohydrodynamic state of the molten pool. Such a research direction is both relevant and justified, as it combines a fundamental mechanical interpretation with the prospect of further experimental optimization and engineering application of the model.

Research objective

The objective of this study is to develop a generalized theoretical approach for describing the influence of shielding gas composition on the geometry of the deposited layer in the WAAM process. To achieve this objective, the following tasks were formulated: to establish a cause-and-effect framework describing the influence of the gaseous environment on the thermal state of the arc and the thermocapillary response of the molten pool; to introduce integral indices characterizing the thermophysical and chemical-surface properties of the gas mixture; and to construct the structure of a semi-empirical model for describing bead width, layer height, and penetration depth.

The criteria for evaluating the quality of the obtained results include the physical validity of the approach, the internal consistency of the model, and its suitability for further parametric identification. The limitations of the study are determined by its theoretical nature, the use of a reduced analytical description, and its focus on arc-based WAAM processes operating in shielding gas environments.

Materials and research methodology

The material of the study consists of scientific publications devoted to WAAM technology, the influence of

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shielding gas composition on arc processes, thermocapillary phenomena in the weld pool, and thermohydrodynamic modeling of molten pools [1–15]. The analysis includes review studies on WAAM [1–5], investigations of the influence of shielding gas in WAAM [6–9, 15], works on classical welding processes addressing the effects of gas mixtures on arc behavior, metal transfer, and weld pool morphology [10, 11, 14], as well as studies on numerical modeling of heat transfer and molten metal flow [12, 13].

The research methodology is based on a sequential transition from the analysis of known physical mechanisms to the development of a reduced analytical model. At the first stage, literature data were systematized concerning the influence of shielding gas composition on bead geometry, arc stability, metal transfer, and flow behavior in the molten pool. At the second stage, these patterns were physically generalized with the identification of two principal channels through which the gaseous environment influences the process: the thermophysical channel and the chemical–surface channel. At the third stage, a cause-and-effect framework of the process was established, and integral indices were introduced to parameterize the identified mechanisms of influence. At the final stage, the structure of a semi-empirical model was constructed to describe bead width, layer height, and penetration depth.

The study employed the method of scientific literature analysis, physical modeling of the process based on the principles of continuum mechanics, and a semi-empirical mathematical description. The analytical method was used to identify stable and physically justified relationships describing the influence of He, CO_2, and O_2 on the thermal state of the arc, the surface activity of the molten metal, and the geometry of deposition [6–11, 14, 15]. Physical modeling was applied to determine the principal mechanisms governing the formation of layer geometry, which are reduced to variations in effective heat input, the thermocapillary response of the molten pool, and the mass balance of deposited metal [11–13]. The semi-empirical approach was used to formalize the relationship between gas mixture composition and the main geometric characteristics of the deposited layer.

To describe the influence of the gaseous environment, two integral indices were introduced. The gas thermophysical index (GTI) characterizes the generalized influence of the gas mixture on the thermal state of the arc, whereas the gas activity index (GAI) reflects its influence on the surface state of the molten metal and on the conditions governing thermocapillary convection. Within the proposed model, effective heat input is considered as a function of process parameters and GTI, while the thermocapillary response of the molten pool is described as a function of GAI. Bead width and penetration depth are represented as functions of the thermal state and flow behavior in the molten pool, whereas layer height is determined through the mass balance of deposited material and the geometry of the cross-section.

The reliability and validity of the obtained results are ensured by the physical interpretability of all model parameters, the consistency of the model with the conservation laws of mass, energy, and momentum, and its agreement with established trends reported in the literature for inert, helium-containing, and active gas mixtures [6–12, 14, 15]. The proposed approach has a theoretical character and is intended to describe the macrogeometry of the deposited layer at the level of integral characteristics. It does not replace full three-dimensional numerical modeling but provides a conceptual foundation for further calibration and application in predictive and optimization tasks for the WAAM process.

Research results

In this study, the results were obtained through the construction and analytical investigation of a semi-empirical model describing the formation of the geometry of a single deposited bead in WAAM. Within the proposed formulation, the composition of the shielding gas is taken into account through two integral parameters, namely the gas thermophysical index $\boldsymbol{GTI}$ and the gas activity index $\boldsymbol{GAI}$, which represent, respectively, the thermophysical and chemical–surface channels through which the gaseous environment influences the deposition process. This approach makes it possible to establish a functional relationship between the properties of the gas environment, the thermal state of the arc, the thermocapillary response of the molten pool, and the principal geometric characteristics of the formed layer.

In what follows, the geometry of the current bead is described by four principal cross-sectional parameters: bead width $\boldsymbol{w}$, layer height $\boldsymbol{h}$, penetration depth $\boldsymbol{p}$ and wetting angle $\boldsymbol{\theta}$. The width $\boldsymbol{w}$ is defined at the level of the surface of the previous layer, the height $\boldsymbol{h}$ - as the distance from this surface to the apex of the current bead, and the penetration depth $\boldsymbol{p}$ - as the distance from the same reference surface to the lowest point of the fusion zone. The wetting angle $\boldsymbol{\theta}$ characterizes the geometry of contact between the current layer and the previous one and reflects the spreading conditions of the liquid metal over the deposition surface. In the model, this parameter is of fundamental importance, since it is through $\boldsymbol{\theta}$ that the geometry of the bead cross-section is made consistent with the mass balance of the deposited metal.

The construction of the model is based on the assumption that the influence of shielding gas on deposition geometry is realized through variations in two governing components of the process. The first is associated with changes in the thermal state of the arc and the effective heat input to the deposition zone, while the second is associated with changes in the surface state of the molten pool and the character of thermocapillary flow. Accordingly, the model separately describes the energetic mechanism and the surface-hydrodynamic mechanism of bead geometry formation.

The basic energetic characteristic of the process is taken to be the linear heat input

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$$Q_l = \eta_0 \frac{UI}{v_t}, \quad (1)$$

where Q_l is the linear heat input, J/m; η_0 is the thermal efficiency coefficient of the process; U is the arc voltage, V; I is the welding current, A; and v_t is the torch travel speed, m/s.

Taking into account the influence of the gaseous environment, the effective linear heat input is written as

$$Q_{eff} = Q_l\left[1 + c_g(GTI - 1)\right], \quad (2)$$

where Q_{eff} is the effective linear heat input, J/m; c_g is the sensitivity coefficient of heat input to changes in the thermophysical properties of the gas mixture.

The chemical-surface influence of the shielding gas is taken into account through the thermocapillary response function

$$\Psi_M = tanh[\chi(GAI - GAI_{cr}], \quad (3)$$

where Ψ_M is the dimensionless thermocapillary response function; GAI_{cr} is the critical value of the gas activity index; and χ is a parameter determining the steepness of the transition between flow regimes in the molten pool.

To account for the energy required for metal melting, a characteristic linear scale is introduced:

$$L_m = \sqrt{\frac{Q_{eff}}{\rho H_m}}, \quad (4)$$

where L_m is the characteristic melting scale, m; ρ is the metal density, kg/m^3; and H_m is the effective specific enthalpy of melting, J/kg.

Then the bead width is described by the relation

$$w = K_w L_m(1 - d_w\Psi_M), \quad (5)$$

and the penetration depth by

$$p = K_p L_m(1 + d_p\Psi_M), \quad (6)$$

where K_w, K_p, d_w, d_p are dimensionless model parameters. Equation (5) reflects that an increase in the melting scale broadens the bead, whereas an increase in Ψ_M, that is, a transition toward inward flow, limits its lateral spreading. Equation (6), in contrast, shows that the same transition promotes deeper penetration due to the concentration of heat and mass transfer in the axial zone.

The cross-sectional area of the bead is determined from the mass balance:

$$A_b = \frac{\dot{m}}{\rho v_t}, \quad (7)$$

where A_b – is the cross-sectional area, m^2; and $\dot{m}$ is the deposition mass rate, kg/s.

To establish the relationship between A_b, w, h and θ the bead cross-section is approximated by a symmetric circular segment. In this case, the cross-sectional area is

$$A_b = \frac{w^2}{4\,sin^2\theta}(\theta - sin\theta cos\theta), \quad (8)$$

where θ is expressed in radians, and the bead height is determined by

$$h = \frac{w}{2}\tan\frac{\theta}{2}, \quad (9)$$

Thus, the wetting angle θ enters the model as a geometric parameter through which the mass balance and the cross-sectional shape are closed. This makes it possible to determine the layer height not as an independent quantity, but as a consequence of the simultaneous action of mass input, bead width, and wetting conditions.

To evaluate morphological repeatability, the standard deviation of width was used:

$$\sigma_w = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(w_i - \bar{w})^2}, \quad (10)$$

where w_i are the local width values, $\bar{w}$ is the mean width, and N is the number of considered cross-sections. Within the developed model, σ_w is used as an integral indicator of formation stability, sensitive to changes in the molten pool flow regime.

The resulting system of relations

$$\{x_i\} \rightarrow GTI,\, GAI \rightarrow Q_{eff},\, \Psi_M \rightarrow w,\, p \rightarrow \theta \rightarrow\; h \rightarrow \sigma_w (11)$$

defines the complete structure of the model and provides a basis for the analytical investigation of the influence of shielding gas on the morphology of a single bead.

From Eq. (2), it directly follows that

$$\frac{\partial Q_{eff}}{\partial GTI} = Q_l\, c_g > 0. \quad (12)$$

Therefore, for positive c_g an increase in GTI leads to an increase in the effective linear heat input. Then, from Eq. (4),

$$\frac{\partial L_m}{\partial GTI} > 0, \quad (13)$$

and from Eq. (5),

$$\frac{\partial w}{\partial GTI} > 0. \quad (14)$$

This means that an increase in the gas thermophysical index, corresponding to a stronger thermophysical effect of the gas mixture on the arc, leads to bead widening.

From Eq. (6), it simultaneously follows that

$$\frac{\partial p}{\partial GTI} > 0, \quad (15)$$

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that is, penetration depth also increases with increasing $\boldsymbol{GTI}$. However, within the framework of the model, this effect is determined primarily by the increase in the melting scale $\boldsymbol{L_m}$, rather than by a restructuring of surface flows.

For constant $\boldsymbol{\dot{m}}$, $\boldsymbol{\rho}$ and $\boldsymbol{v_t}$ the cross-sectional area $\boldsymbol{A_b}$ remains constant according to Eq. (7). Therefore, an increase in $\boldsymbol{w}$ at constant $\boldsymbol{A_b}$ is possible from Eq. (8) only due to a decrease in the wetting angle:

$$\frac{\partial\theta}{\partial GTI} < 0. \tag{16}$$

Further, from Eq. (9),

$$\frac{\partial h}{\partial GTI} < 0. \tag{17}$$

Hence, an increase in $\boldsymbol{GTI}$ within the model leads to the formation of a wider, lower, and less convex bead with a smaller wetting angle.

For the thermocapillary response function, Eq. (3) yields

$$\frac{\partial\Psi_M}{\partial \mathrm{GAI}} = \chi\,\mathrm{sech}^2[\chi(GAI - GAI_{cr})] > 0. \tag{18}$$

This means that, with increasing $\boldsymbol{GAI}$ the system monotonically transitions from a regime of predominantly outward flow to a regime of inward flow.

From Eq. (5), one obtains

$$\frac{\partial \mathrm{w}}{\partial \mathrm{GAI}} < 0, \tag{19}$$

and from Eq. (6),

$$\frac{\partial \mathrm{p}}{\partial \mathrm{GAI}} > 0. \tag{20}$$

Thus, an increase in gas activity leads to a narrowing of the bead and an increase in penetration depth. This is a direct consequence of the fact that inward flow reduces lateral spreading of the metal and promotes axial concentration of the heat flux.

Since, at constant $\boldsymbol{A_b}$ bead narrowing must be compensated by an increase in the convexity of the cross-section, Eq. (8) implies

$$\frac{\partial \theta}{\partial \mathrm{GAI}} > 0. \tag{21}$$

Then, from Eq. (9),

$$\frac{\partial \mathrm{h}}{\partial \mathrm{GAI}} > 0. \tag{22}$$

Thus, within the framework of the model, an increase in $\boldsymbol{GAI}$ leads to the formation of a narrower, higher, and more convex bead with a larger wetting angle and greater penetration.

Expression (18) reaches its maximum under the condition

$$GAI = GAI_{cr}. \tag{23}$$

This means that precisely in the vicinity of $\boldsymbol{GAI = GAI_{cr}}$ the geometric parameters of a single bead are most sensitive to variations in gas composition. Hence, the model predicts a nonlinear, threshold-type character of the influence of active gas components on layer morphology. Outside this region, the sensitivity decreases, since the $\boldsymbol{tanh}$ function approaches saturation.

A combined analysis of Eqs. (5)–(9) shows that the geometry of a single bead is determined by the competition between two mechanisms. The first mechanism is associated with an increase in $\boldsymbol{GTI}$, which raises the effective heat input, the melting scale, and the bead width. The second mechanism is associated with an increase in $\boldsymbol{GAI}$, which, through $\boldsymbol{\Psi_M}$ alters the character of surface flows, narrows the bead, increases its convexity, and deepens penetration.

An important result follows from this: the same bead width may be obtained for different combinations of $\boldsymbol{GTI}$ and $\boldsymbol{GAI}$, but with different values of$\boldsymbol{p}$, $\boldsymbol{\theta}$ and $\boldsymbol{h}$. Therefore, the morphology of the deposited layer cannot be correctly described by the single parameter $\boldsymbol{w}$ alone; instead, it is necessary to consider the interrelated system

$$\{w,\ h,\ p,\ \theta\}. \tag{24}$$

The developed model further implies that the greatest instability in geometric formation should manifest itself in the vicinity of the critical region $\boldsymbol{GAI_{cr}}$, where the sensitivity of width and wetting angle to gas composition is maximal. It is precisely in this region that local fluctuations in the thermocapillary response will exert the strongest influence on $\boldsymbol{\sigma_w}$, i.e., on waviness and geometric repeatability from layer to layer.

Thus, the analytical investigation of the developed model has shown that

$$GTI \uparrow \Rightarrow Q_{eff} \uparrow, w \uparrow, p \uparrow, \theta \downarrow, h \downarrow \tag{25}$$

$$GAI \uparrow \Rightarrow \Psi_M \uparrow, w \downarrow, p \uparrow, \theta \uparrow, h \uparrow, \tag{26}$$

$\boldsymbol{GAI \approx GAI_{cr}}$ ⇒ maximum sensitivity $\boldsymbol{w}$, $\boldsymbol{h}$, $\boldsymbol{p}$, $\boldsymbol{\theta}$ to gas composition. (27)

Therefore, the principal result of the study is the development and analytical treatment of a dimensional model for the formation of the geometry of a single deposited bead in WAAM, in which bead width, layer height, penetration depth, and wetting angle are linked into a unified system through mass balance, effective heat input, and the thermocapillary response of the molten pool. The obtained relationships define the nature of the influence of shielding gas composition on bead morphology and provide a basis for further experimental calibration of the model and physical interpretation of the results.

In the present study, the proposed model was formulated for Fe-based WAAM, primarily for steel systems, in which the influence of shielding gas composition on bead width, penetration depth, wetting angle, and layer height can be generalized within the framework of a thermophysical–surface formulation.

For the practical interpretation of the obtained dependencies, Table 1 presents the generalized character of the influence of typical shielding gas environments on the geometry of a single deposited bead in Fe-based WAAM. The table reflects the expected morphological trends within the framework of the developed model.

Discussion

The obtained results indicate that the influence of shielding gas composition on the geometry of the deposited layer in WAAM should be considered as the result of the combined action of two physically distinct mechanisms. The first mechanism is associated with changes in the thermal state of the arc and the effective linear heat input, while the second is related to variations in the surface state of the molten pool and the character of thermocapillary flow. Such a separation makes it possible to move beyond a purely technological interpretation of the gaseous environment and to consider it instead as a control factor that directly affects the morphology of an individual bead.

It should be emphasized that the applied interpretation of the model presented here primarily concerns Fe-based WAAM, for which the influence of shielding gas on the geometry of a single bead can be generalized through thermophysical and chemical–surface mechanisms.

From the standpoint of process physics, the obtained relationships for $\boldsymbol{Q_{eff}}$, $\boldsymbol{w}$ and $\boldsymbol{p}$ are consistent with the fact that the thermophysical properties of the gas mixture determine not only the overall level of supplied energy but also the character of its spatial distribution in the arc region. Within the framework of the model, an increase in the thermophysical index $\boldsymbol{GTI}$ leads to an increase in the effective linear heat input and, consequently, in the characteristic melting scale $\boldsymbol{L_m}$. This can be interpreted as an expansion of the thermal influence zone and an increase in bead width. Such a result is physically plausible for gas mixtures with higher thermophysical potential, particularly those containing helium, where the plasma column and heat flux become more distributed, resulting in a wider and less convex bead.

At the same time, the model shows that an increase in $\boldsymbol{GAI}$ affects not the energetic component of the process, but primarily its surface-hydrodynamic component. Through the function $\boldsymbol{\Psi_M}$ this reflects a transition from a regime of predominantly outward flow to a regime of inward redistribution of the molten metal. Within this formulation, an increase in $\boldsymbol{GAI}$ naturally leads to a decrease in bead width and an increase in penetration depth. The physical meaning of this result lies in the fact that active components of the gaseous environment, by altering the surface state of the melt, affect the sign and magnitude of the thermocapillary gradient and, consequently, the direction of surface flows in the molten pool. As a result, heat and liquid metal become concentrated in the axial zone, which promotes the formation of a narrower but more deeply penetrated bead.

In the developed model, the wetting angle $\boldsymbol{\theta}$ does not serve as a secondary or merely illustrative parameter. On the contrary, it is precisely through this parameter that the geometry of the bead cross-section is made consistent with the mass balance of the deposited metal. This means that a change in width $\boldsymbol{w}$ at constant mass input cannot be considered in isolation from a change in cross-sectional shape. If $\boldsymbol{GTI}$ increases and the bead widens, then, at constant $\boldsymbol{A_b}$ this must be accompanied by a decrease in $\boldsymbol{\theta}$, that is, by the formation of a flatter profile. If, by contrast, $\boldsymbol{GAI}$ increases and the bead narrows, this should lead to an increase in $\boldsymbol{\theta}$ and to more pronounced convexity. For this reason, inclusion of the wetting angle in the model is necessary for a mechanically consistent description of the layer height $\boldsymbol{h}$.

The obtained equation for $\boldsymbol{h}$ has important methodological significance. Unlike many empirical approaches in which layer height is specified by a separate regression relationship, in the present work it is determined through the cross-sectional area, bead width, and wetting angle. This makes the description physically consistent: layer height is not an independent variable but rather a consequence of the combined action of heat input, surface phenomena, and mass transfer. From this standpoint, the developed model better corresponds to the real nature of WAAM, where the geometry of a single layer cannot be adequately described by a single parameter without taking into account the shape of the cross-section. The presence of the parameter $\boldsymbol{GAI_{cr}}$ in the model means that the influence of active components of the gas mixture on bead geometry has a threshold character. The maximum sensitivity of geometry to gas composition is realized precisely in the vicinity of $\boldsymbol{GAI_{cr}}$, where the derivative $\boldsymbol{\partial\Psi_M/\partial GAI}$ reaches its maximum. In physical terms, this corresponds to the region in which a change in the surface state of the melt produces the most intensive restructuring of flow in the molten pool. For WAAM, this is particularly important because, in a multilayer process, even a moderate variation in the geometry of a single pass accumulates and affects the dimensional accuracy of subsequent layers.

The developed model also leads to another important implication: the same value of bead width may be achieved by different combinations of $\boldsymbol{GTI}$ and $\boldsymbol{GAI}$, but with different values of $\boldsymbol{p}$, $\boldsymbol{h}$ and $\boldsymbol{\theta}$. This means that focusing on only one morphological parameter, for example bead width, is insufficient for evaluating the quality of the gaseous environment. A gas mixture that provides an acceptable value of $\boldsymbol{w}$, does not necessarily ensure optimal penetration, wetting angle, or formation stability. That is why, in the present work, the morphology of a single bead is considered as a system of interrelated parameters $\{\boldsymbol{w}, \boldsymbol{h}, \boldsymbol{p}, \boldsymbol{\theta}\}$, rather than as a set of independent quantities.

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Table 1 – Applied interpretation of the model for typical shielding gas environments in Fe-based WAAM

Typical shielding gas environment	Expected GTI level	Expected GAI level	Dominant mechanism within the model	Expected geometry of a single bead	Applied interpretation for Fe-based WAAM
Pure argon (Ar = 99.9–100%)	reference	very low	Baseline thermal state of the arc under minimal chemical–surface influence	w – medium; h – medium; p – moderate; θ – medium	Can be treated as the baseline inert atmosphere for comparison with He-containing and active-gas mixtures
Ar-He, He-enhanced inert environment (Ar + 10–25% He)	elevated	low	Strengthening of the thermophysical channel: increase in Q_{eff} and L_m	$w\uparrow$; $h\downarrow$; $p\uparrow$; $\theta\downarrow$	A wider, lower, and less convex bead is expected. Such mixtures are suitable when enhanced spreading of molten metal and a flatter layer profile are required
Ar + low O_2 addition (Ar + 1–2% O_2)	close to reference or slightly increased	moderate	Strengthening of the chemical–surface channel and modification of the thermocapillary gradient	$w\downarrow$; $h\uparrow$; $p\uparrow$; $\theta\uparrow$	Can be interpreted as a controlled means of narrowing the bead and increasing penetration without moving to a strongly active atmosphere.
Ar + low moderate CO_2 addition (Ar + 2–5% CO_2)	close to reference or slightly increased	moderate / moderately elevated	Chemical–surface influence of the active component with enhanced inward thermocapillary flow	$w\downarrow$; h ↑; p ↑; θ ↑	This is a practically important range for Fe-based WAAM: the bead becomes narrower, higher, and more deeply penetrated; in many cases, this range provides a useful compromise between geometry and stability
Ar + elevated CO_2 content (Ar + 8–12% CO_2)	moderate	high	Dominance of the chemical–surface mechanism and strong restructuring of molten-pool flow	$w\downarrow\downarrow$; $h\uparrow\uparrow$; $p\uparrow\uparrow$; $\theta\uparrow\uparrow$	A narrow, more convex, and deeply penetrated bead is expected. This range is associated with higher morphological sensitivity to disturbances and reduced repeatability
Combined Ar-He–active gas environment (Ar + 10–20% He + 0.5–2% CO_2 or Ar + 10–20% He + 0.5–1% O_2)	elevated	moderate	Competition of two mechanisms: (GTI) tends to widen the bead, whereas (GAI) tends to narrow it and increase penetration	w – moderate/controllable; h – moderate; $p\uparrow$; θ – close to medium or moderately increased	This is the most flexible category for bead-shape control, since it allows sufficient heat input to be combined with a controlled surface-driven effect

The parameter $\boldsymbol{\sigma_w}$, which characterizes formation repeatability, is not directly included in the main system of analytical equations in this study; however, the model makes it possible to interpret its behavior. Since, in the vicinity of $\boldsymbol{GAI_{cr}}$ bead geometry is most sensitive to small changes in the gaseous environment, it is precisely in this region that increased nonuniformity of formation and a rise in $\boldsymbol{\sigma_w}$ can be expected. Thus, the model not only describes the average geometric parameters of a single bead, but also provides a physical explanation of why the stability of the multilayer process may deteriorate under conditions close to critical thermocapillary restructuring.

At the same time, the results should be interpreted with due regard for the limits of applicability of the proposed formulation. The model is reduced in nature and does not fully account for arc unsteadiness, the discrete nature of droplet transfer, the temperature dependence of all metal and gas properties, or the specific features of particular alloys, which may influence the critical value $\boldsymbol{GAI_{cr}}$. It also does not replace a full three-dimensional CFD description of the process. Nevertheless, precisely as an analytical generalized framework, it has a significant advantage: it makes it possible to consider shielding gas composition as a model parameter rather than merely as a background experimental condition.

Therefore, the modeling results show that the formation of the geometry of a single deposited bead in WAAM is governed by the competition between two mechanisms: the expansion of the melting scale under the influence of the thermophysical properties of the gas, and the restructuring of thermocapillary flow under the influence of its chemical activity. It is this competition that determines whether a wider and flatter bead is formed, or a narrower, higher, and more deeply penetrated layer. This

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constitutes the principal physical significance of the developed model and underlies its suitability as a basis for further experimental calibration.

Conclusions

A semi-empirical model describing the formation of the geometry of a single deposited bead in WAAM has been developed, in which the composition of the shielding gas is incorporated through two integral parameters: the gas thermophysical index $\boldsymbol{GTI}$ and the gas activity index $\boldsymbol{GAI}$. The proposed approach makes it possible to relate the properties of the gaseous environment to the effective heat input, the thermocapillary response of the molten pool, and the geometry of the bead.

It has been shown that the geometry of a single bead should be considered as an interconnected system of parameters $\boldsymbol{w}$, $\boldsymbol{h}$, $\boldsymbol{p}$ and $\boldsymbol{\theta}$, where bead width $\boldsymbol{w}$, layer height $\boldsymbol{h}$, penetration depth $\boldsymbol{p}$ and wetting angle $\boldsymbol{\theta}$ are determined by the combined action of thermal, surface, and mass transfer processes. The inclusion of the wetting angle in the model ensures consistency between the cross-sectional geometry and the mass balance of the deposited metal.

Analysis of the model has demonstrated that an increase in $\boldsymbol{GTI}$ leads to an increase in effective linear heat input, bead widening, and a reduction in bead convexity, whereas an increase in $\boldsymbol{GAI}$ results in bead narrowing, greater penetration depth, increased layer height, and a larger wetting angle. It has been established that the highest sensitivity of the geometric parameters to shielding gas composition occurs in the vicinity of the critical value $\boldsymbol{GAI_{cr}}$.

The practical significance of the obtained results lies in providing a theoretical foundation for further calibration of the model, for the rational selection of shielding gas composition, and for the development of approaches to controlling the geometry of the deposited layer in WAAM. Further research should focus on experimental validation of the model and on the identification of its parameters for specific material–process–gas environment systems.

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МОДЕЛЮВАННЯ ВПЛИВУ СКЛАДУ ЗАХИСНОГО ГАЗУ НА ГЕОМЕТРІЮ НАПЛАВЛЕНОГО ШАРУ ПРИ ТЕХНОЛОГІЇ ДУГОВОГО АДИТИВНОГО ВИРОБНИЦТВА З ВИКОРИСТАННЯМ ДРОТУ (WAAM)

Руслан Куликовський – канд. техн. наук, доцент, проректор з науково-педагогічної роботи та питань перспектив розвитку університету Національного університету «Запорізька політехніка», м. Запоріжжя, Україна, *e-mail: kulikovski@zp.edu.ua*, ORCID: 0000-0001-8781-2113

Кирил Красносельський – аспірант кафедри інтегрованих технологій зварювання та моделювання конструкцій Національного університету «Запорізька політехніка», м. Запоріжжя, Україна, *e-mail: kvkras@gmail.com*, ORCID: 0009-0006-5251-9076

Мета роботи. *Розроблення узагальненого теоретичного підходу до опису впливу складу захисного газу на геометрію наплавленого шару при технології WAAM з урахуванням теплофізики дуги, поверхневих явищ та термогідродинаміки зварювальної ванни.*

Методи дослідження. *Використано методи аналізу й узагальнення наукових публікацій, положення теорії теплопереносу та механіки рідини з вільною поверхнею, фізичне моделювання термокапілярної конвекції, а також метод напівемпіричного математичного опису із введенням інтегральних індексів газового середовища.*

Отримані результати. *Сформовано причинно-наслідкову схему впливу складу захисного газу на ефективне тепловкладення, поверхневу активність розплаву та геометричні параметри наплавленого шару. Запропоновано термофізичний індекс газу GTI, що характеризує вплив газової суміші на тепловий стан дуги, та індекс газової активності GAI, який відображає вплив активних компонентів на термокапілярну відповідь ванни розплаву. Побудовано структуру напівемпіричної моделі, яка пов'язує склад газу з шириною валика, висотою шару та глибиною проплавлення.*

Наукова новизна. *Запропоновано інтегрований підхід до опису впливу захисного газу на формування геометрії наплавленого шару при WAAM, у якому газове середовище розглядається як фізично змістовний параметр процесу. Уперше в межах даної постановки введено систему інтегральних індексів GTI та GAI для формалізованого врахування хімічно-поверхневого та термофізичного каналів впливу газової суміші.*

Практична цінність*. Отримані результати можуть бути використані як теоретична основа для вибору складу захисного газу, прогнозування геометрії наплавленого шару, подальшої калібровки моделі за експериментальними даними та розроблення алгоритмів керування процесом WAAM.*

Ключові слова: *технологія дугового адитивного виробництва з використанням дроту (WAAM), захисний газ, наплавлений шар, геометрія валика, термокапілярна конвекція, зварювальна ванна, математичне моделювання, проплавлення.*

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