Transferability of the working envelope approach for parameter selection and optimization in thin wall WAAM

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Abstract

This work aims to propose and assess a methodology for parameterization for WAAM of thin walls based on a previously existing working envelope built for a basic material (parameter transferability). This work also aimed at investigating whether the working envelope approach can be used to optimize the parameterization for a target wall width in terms of arc energy (which governs microstructure and microhardness), surface finish and active deposition time. To reach the main objective, first, a reference working envelope was developed through a series of deposited walls with a plain C-Mn steel wire. Wire feed speed (WFS) and travel speed (TS) were treated as independent variables, while the geometric wall features were considered dependent variables. After validation, three combinations of WFS and TS capable of achieving the same effective wall width were deposited with a 2.25Cr-1Mo steel wire. To evaluate the parameter transferability between the two materials, the geometric features of these walls were measured and compared with the predicted values. The results showed minor deviations between the predicted and measured values. As a result, WAAM parameter selection for another material showed to be feasible after only fewer experiments (shorter time and lower resource consumption) from a working envelope previously developed. The usage of the approach to optimize parameterization was also demonstrated. For this case, lower values of WFS and TS were capable of achieving a better surface finish. However, higher WFS and TS are advantageous in terms of production time. As long as the same wall width is maintained, variations in WFS and TS do not significantly affect microstructure and microhardness.

Keywords WAAM · Working envelope · Parameterization · Parameter transferability · Optimization

1 Introduction

Wire arc additive manufacturing (WAAM) has gained momentum as a group of processes capable of achieving high deposition rates when compared with other AM processes applied to metals. WAAM processes also stand out for their great versatility in terms of metallic materials, ranging from high-strength low alloy (HSLA) steels [1–3] to Ni-rich alloys [4]. From the development side, according to Wu et al. [5], depending on the version, Gas Metal Arc (GMA) can reach deposition rates between 2 and 3 times higher than Gas Tungsten Arc (GTA) and Plasma Arc (PA). Williams et al. [6] pointed out that GMA allows for more accessible trajectory programming due to the coaxiality between wire and torch. These characteristics make GMA prominent for the fabrication of metallic components in a relatively short time. Despite the advantages, the application of GMA as a power drive in WAAM requires time and resources to find

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adequate operational parameters and provide proper geometric features, surface finish and material properties. From the end-user side, a body of experts for process parameterization is not desirable (out of the business core field). End-users need to satisfy their clients with short delivery times and attending custom orders. They do not want to carry out many experiments to define parameters for this specific technology. Thus, harnessing strategies for cost and time-effective parameterization is crucial for maturing this technology in terms of acceptance from industrial end-users.

In this scenario, the operational map application can be pointed as a potential solution, allowing the prediction of parameter ranges capable of meeting the requirements for the mentioned aspects. This approach was successfully used in the past for welding and overlaying operations. But still not fully explored for WAAM, to the best of the authors' knowledge. In the working envelope approach, the process parameters are assumed as independent variables and are usually systematically varied, following an experimental design. According to the analysis objective, the variables of interest (dependent variables), such as geometry or discontinuities, are assessed quantitatively or qualitatively. In some cases, the construction of such maps allows for the development of equations and contour plots for predictions.

Following this approach, Marinelli et al. [7] built a working envelope for autogenous welding with GTAW, evaluating different levels of travel speed and shielding gas compositions (varying Argon and Helium contents). The authors found that higher He contents in the shielding gas and lower travel speeds resulted in weld beads free of cracks. In another work, Ahsan et al. [8] investigated the viability of applying Cold Metal Transfer (CMT) GMAW to weld overlap joints without any gaps. According to the authors, two working envelopes were identified in terms of porosity and mechanical properties: one for low heat input (200 to 250 J/mm) and another for high heat inputs (350 to 550 J/mm). Dye et al. [9] conducted a numerical analysis to predict parameter combinations (effective power and travel speed) capable of avoiding lack of penetration, porosity, liquation cracks and solidification cracks for welding a nickel superalloy (IN718)

with GTAW. The authors proposed a weldability map and identified a region characterized by proper weld features (working envelope) based on the results.

In additive manufacturing, some developments approached operational maps, mainly when Laser is used as a power source. Thomas et al. [10], for instance, compiled literature data for different materials deposited by powder bed fusion (PBF), aiming at avoiding porosity, voids and solidification cracks. Similarly, Dass and Moridi [11] also compiled literature data for materials deposited by direct energy deposition (DED) with Laser. This latter study built a map considering heat input and powder feed rate as independent variables; three regions of non-conformity incidences (keyholing, lack of fusion and porosity) were identified. As one of the pioneers in terms of parameterization for WAAM, Martina et al. [12] developed a working envelope for the Plasma Arc to prevent the formation of different geometric irregularities in walls deposited with a Ti alloy. At the end of the study, they proposed a statistical model capable of maximizing the layer height and deposition rate for a given effective wall width, aiming to select process parameters.

As can be seen, the use of working envelopes in the context of the operational maps follows the same principle, yet with different objectives. In the case of WAAM, there is the goal of achieving a determined dimension in the construction of the component. Thereby, different from other applications, including welding and overlaying, the authors of the present paper conceive that the maps for these processes should consider the wall width as a dependent variable (which is the starting point for an AM build design), whilst wire feed speed (WFS) and travel speed (TS) are considered independent variables (electric current can also be used replacing WFS). For illustration matters of the authors' proposal, Fig. 1a represents an operational map, which comprehends a global universe of parameters. The working envelope represents the region within the map where the parameter combinations provided results that meet given acceptance criteria. Figure 1b, in turn, exemplifies the parameter selection. As can be noticed, different combinations of WFS and TS (points I, II and III) can be established

Fig. 1 (a) Representation of an operational map and (b) parameter selection plan within a working envelope

Fig. 2 Working envelopes for WAAM of thin walls built using data from Da Silva et al. [13] and Dahat et al. [14]

to achieve the same target width (W). Hypothetically, the parameter combination labelled as “I” can be the one that results in a better surface finish. Combination “II” might be the one that guarantees a more robust product (since it is distant from the boundaries of the envelope). Combination “III” would potentially reach a shorter deposition time. Therefore, selecting one of the parameter combinations depends on each characteristic priority level.

In summary, a working envelope can be used not just to find a process parameter window that avoids non-conformities (as usually this concept is applied for). However, it is also applicable for optimization targeting specific characteristics. In this context, the same research group of this proposal built a working envelope for WAAM using an Al-5Mg alloy as feedstock [13]. The acceptance criteria to delimit the working envelope took into account surface aspect, surface waviness (< 0.5 mm) and porosity formation (< 3.0 %). Complementarily, Da Silva et al. [13] introduced a model of the working envelope, visualized by contour plots for total width, effective width and layer height, as a function of WFS and TS. Also exploring the potentiality of operational maps for WAAM by the same group, Dahat et al. [14] earlier described a step-by-step methodology for the construction of working envelopes. As a case study, they used a HSLA steel deposited with CMT. By comparing the predicted dependent variables with those experimentally found, the authors proved a high reputability capable of validating the proposed methodology.

Figure 2 presents a compilation of the working envelopes built by Da Silva et al. [13] and Dahat et al. [14] for an Al-5Mg alloy and an HSLA steel, respectively. As can be seen, despite the use of very distinct materials, both working envelopes present essentially the same format. However, the working

envelopes assumed different positions within the operational map since the boundaries changed according to the material and other process variables. Examples of essential variables in this context can be shielding gas, wire diameter, contact tube to work distance (CTWD), interlayer temperature, thermal management method (forced cooling) and even arbitrary acceptance criteria adopted to construct the maps. Nevertheless, this finding indicates that it could be possible to use a pre-existing envelope to find parameters for another material.

As evidenced by Da Silva et al. [13] and Dahat et al. [14], the working envelope approach shows itself as a robust and practical tool for parameter selection in thin WAAM. The concept of thin walls considers single beads per layer, with no torch oscillation in the transverse direction. However, it still demands experimental work (time and resource consuming) to be raised. Aiming at making this approach more cost-effective and functional, the main objective of this work is to verify the possibility of parameterizing thin walls deposited by WAAM for a feedstock, based on a pre-existing working envelope made with a different and ordinary (cheaper) material. As a complementary objective, it aims at investigating whether or not the working envelope can be used to optimize parameter selection of a target wall width, in terms of operational characteristics (objective functions), such as surface finish, active deposition time, arc energy (which governs microstructure and microhardness). Here, the surface finish is understood as that resulted from the deposition, with no after work (machining). As a whole, this proposal tries to contribute to maturing a not widely used methodology for WAAM parameter selection for thin wall WAAM.

2 Methodology and experimental procedures

A working envelope employing a C-Mn steel wire (1.2-mm-diameter wire, AWS ER70-S6 class - Table 1), hereafter named as “reference working envelope”, was developed as a base (pre-existing working envelope) to achieve the main objective. As is well-known, this class of material is trendy in welding constructions, and users dominate the technical application. Moreover, this feedstock is reasonably cheap. Then, it seems to be an ideal material for the “reference working envelope” for structural steels, which demand more experiments to be built. This proposed working envelope is applicable to build multilayered wall-like parts deposited with a single pass per layer. The depositions were carried out using a CNC gantry machine coupled with a Fronius power source.

Table 1 Nominal chemical compositions (in weight %) of the wires used in this work

Wire	C	Mn	Si	Cr	Mo	Fe
AWS ER70S-6	0.08	1.46	0.85	-	-	Bal.
AWS ER90S-B3	0.08	0.95	0.60	2.60	1.00	Bal.

A schematic illustration of the employed experimental rig is shown in Fig. 3. The GMA variant Cold Metal Transfer (CMT) was used as a depositing process (synergic line code CMT 0963). The wire feed speed (WFS) and travel speed (TS) were assumed as independent set variables. They were systematically varied, whilst the geometrical features (external and effective width, layer height and surface waviness) were defined as dependent response variables. Subsequently, validation of the reference envelope was implemented using three combinations of set WFS and TS, targeting the same effective width within the working envelope. The geometry of the walls built in the validation step was analysed and compared with the predictions from the working envelope approach. Besides this, cross-sections of the walls were taken and prepared to verify possible changes in microstructure and microhardness.

Once the reference working envelope had been built, characterized and validated, the parameterization transferability from the reference envelope to another material was evaluated. To do so, only three new walls were deposited with a 2.25Cr-1Mo steel (1.2-mm-diameter wire, AWS ER90S-B3 class – Table 1), using the same set-up and parameters employed in the combinations for the reference envelope validation. The potentiality of transferring the parameters from the reference working envelope to this other material was assessed by comparing the measured results with the predictions. Similarly, the microstructure and microhardness from the 2.25Cr-1Mo deposits were also analyzed. Although both wires used in this work are structural carbon steels, it must be highlighted that these materials have different costs and applications. The low alloy carbon steel, referred here as 2.25Cr-1Mo (AWS ER90S-B3), can be up to four times more expensive. This steel corresponds to a high strength

low alloy (HSLA) steel that has functionality in, for instance, the oil and gas industry, where it is often employed to manufacture flanges and fittings that operate at high temperatures. Besides, since the success of the parameterization transferability is highly dependent on the physicochemical compatibility between materials, working with dissimilar classes of feedstock was not an option in this methodology.

The same procedure proposed by Dahat et al. [14] was followed to build the reference envelope and the walls for the validation/transferability trials. In this procedure, substrates, made of cold-rolled steel bars, were clamped in a fixture with the narrower side facing up. This assembly format aimed at simulating a previously built wall (hereafter referred to as “pre-wall”), with the same width as the wall to be built. All walls reached a minimum deposition height of 40 mm, although the number of layers depended on the parameters for each case. For all the depositions, the shielding gas utilized was a mixture of 96% Ar + 4% CO₂, at a 15 L/min flow rate. The contact tube-to-work distance (CTWD) was also kept constant, at 16 mm.

An infrared pyrometer was used to verify the interlayer temperature, so that this temperature would be kept at around 30 °C for all depositions, regardless of the purpose of the built walls (reference envelope construction, trials for envelope validation or trials for parameter transferability). The interlayer temperature verifications were always carried out at the longitudinal centre point of the top surface of each previously deposited layer. The electric signals (current and voltage) and wire feed speed were monitored in each deposited layer, through an A/D board, at 5 kHz rate and during 8 s. Mean and root mean square (RMS) values of current and voltage were calculated for each wall produced, discarding

Fig. 3 Schematic illustration of the experimental rig: (1) arc welding power source and feedstock feeder, (2) 3D CNC coordinate table (torch motion system), (3) building platform, (4) CNC microprocessor and (6) motor drivers

arc start and arc ending data acquisition regions. Average wire feed speed, mean current (I_m), RMS current (I_{rms}), mean voltage (U_m), RMS voltage (U_{rms}) and arc energy per unit of length were calculated for 10 layers in each wall (10 averages of each mean quantity calculated through the acquisition times in each layer). Arc energy per unit of length was calculated by computing the average instantaneous power (average of the point-by-point product of current and voltage) divided by TS. As already mentioned in the literature [15, 16], the control strategy used by the CMT and its variants lead to differences between set and actual wire feed speeds. Due to this equipment performance, the average wire feed speed values were measured with a properly calibrated encoder (0.1 m/min resolution) attached to the wire feeder, and, for each deposition condition, the set WFS (WFS_{set}) was adjusted to reach the desired actual WFS (WFS_{target}).

2.1 Experimental planning for building the reference working envelope

Although there is a direct relationship between wire feed speed (WFS) and mean current (I_m) in GMA, the CMT welding equipment does not follow the same relation throughout the whole operational range. Thus, the working envelope inside the operational map was built as a function of WFS instead of I_m (more commonly used). Moreover, since set directly in the power source interface, WFS is a more accessible parameter for the operator when compared to I_m , which is a consequence of the WFS together with other variables. A theory described by Yehorov et al. [17] was considered to determine the operating ranges of WFS. The authors claim that high arc pressure should be avoided to prevent the molten pool from running down during thin wall deposition. Thus, lower current levels, still capable of guaranteeing the coalescence between layers, should be privileged in parameterizations. Therefore, preliminary tests were carried out to set WFS so that the I_m values do not surpass 170 A. The three levels of target WFS (WFS_{target}) were 3, 4 and 5 m/min, which resulted in I_m values of around 120, 145 and 170 A, respectively.

To determine the travel speed (TS) range for each WFS_{target} , two acceptance criteria were used. The criteria were based on the surface aspects of the walls deposited in preliminary tests: top surface humps and lateral sagging. Periodic humps throughout the longitudinal direction of the beads usually occur when exceeding TS value is reached (upper range limit). The lower limit of TS was defined based on the slowest possible speed that could be used without lateral sagging. To minimize irregularities and establish more conservative limits, the found lower and upper limits of TS were incremented and decremented in 5.0 cm/min, respectively. The higher the WFS level, the higher the current (arc pressure) and the deposition rate (molten pool

volume). Therefore, the lower limits of TS were not the same at each WFS set, increasing according to each level to avoid lateral sagging. The upper limits of TS, in turn, which prevents humping formation, also increased. Yuan et al. [18] claimed that the humping formation is correlated to a strong molten metal flow with high momentum, mainly affected by arc pressure, electromagnetic force and Marangoni force. As discussed by the authors, the increase in current (due to WFS) leads to a higher arc pressure and, consequently, to a greater impulse on the metal flow, facilitating the humping formation. However, a deeper melt pool is also obtained, which may dissipate the metal flow and, hence, the humps. This statement was based on their results, which showed that a short and deep molten pool is less prone to this defect than a long and shallow pool. Thus, since the TS upper limits were increased with the WFS level, it was assumed in this current work that the metal flow dissipation effect due to a deeper pool was predominant. The experimental planning matrix to build the reference working envelope for the AWS ER70S-6 wire, taken from the above considerations, is presented in Table 2. To ensure uniform distribution within each of the WFS operating ranges, the four selected levels of TS were equally divided.

The experimental design for the combinations of WFS and TS will lead naturally to different wall thicknesses. To satisfy the methodological proposal, substrates with the same width as the wall to be built were used and positioned with the narrower side facing up (as afore seen in Fig. 3). However, commercial bars covering all wall widths are not available. Trying to maintain the heat flow the more uniform as possible throughout the deposited layers, the difference in width between the substrate and the wall must be the lowest possible. One solution would be to machine down each bar to the desired thickness. However, alternatively, few layers with intermediate widths were deposited over the substrates face before the actual walls, following the same strategy adopted by Dahat et al. [14], including a theoretical

Table 2 Experimental planning matrix used to build the reference working envelope

Run	WFS_{target} (m/min)	TS_{actual} (cm/min)
1	3	15.0
2	3	26.7
3	3	38.3
4	3	50.0
5	4	18.3
6	4	33.3
7	4	48.3
8	4	63.3
9	5	21.7
10	5	38.9
11	5	56.1
12	5	73.3

approximation proposed to predict the wall widths as a function of the deposition parameters. Therefore, only two different widths of cold-rolled steel bars, 150 x 50 x 7.9 mm and 150 x 50 x 6.3 mm, were employed as substrates. The commercial bar widths were selected to minimize the number of intermediate layers required, aiming at the smallest possible difference between substrate and wall widths. The following criteria were considered to deposit intermediate layers:

- A difference in width up to 1 mm between substrate and wall could be capable of maintaining a constant heat flow.
- When the difference between substrate and wall width predicted was smaller than 1 mm, no intermediate layer was deposited.
- When this difference was between 1 and 2 mm, one intermediate layer was deposited.
- When this difference was between 2 and 3 mm, two intermediate layers were deposited.

2.2 Determination of the geometrical wall features

All the deposited walls were digitalized through a metrology-grade 3D scanner (HandySCAN 3D™). The three geometrical features were measured based on the digital mesh of each wall, via dedicated software (VXElements). They are the external wall width (WW_{ext}), which corresponds to the broadest distance found between the wall sides, the effective wall width (WW_{eff}), which is the smallest distance between the wall sides, and the surface waviness (SW) calculated as the difference between WW_{ext} and WW_{eff} divided by two. For better sampling, the wall sides were split into two meshes and point-by-point measurements of distance between the two surfaces were taken. Figure 4 illustrates a

schematic of the procedure used to quantify the geometrical features. The wall ends (arc start and arc ending regions) were discarded (Fig. 4a), since they tend to be unstable regions. Thus, only a central part of the walls, however long enough (28 x 90 mm), was considered for measurement. Based on the analysis of the WFS signals, a few regions with significantly deviated values was observed, probably due to the control made by CMT to compensate for variations in arc length caused by irregularities throughout the deposition of a layer. To avoid the influence of such non-common regions in the geometry assessment, the aforementioned central regions of the walls were divided into three equally spaced slices (28 x 30 mm each) along the wall length (Fig. 4b) and some outliers resultant from these WFS variations were neglected. In Fig. 4c, for instance, the external width value of 9.5 mm was not considered, since it corresponds to an outlier. In this way, for the given example, the largest width registered was 8.6 mm. Based on this methodology for each slice, a single value of WW_{ext} , WW_{eff} and SW was taken, representing the corresponding average value of each measurement. The layer heights (LH) were quantified by measuring the total wall heights with a Vernier calliper, at five different positions, and then dividing by the number of deposited layers.

2.3 Metallurgical and chemical characterization

One cross-section was taken from each wall from the validation (AWS ER70S-6) and the transferability (AWS ER90S-B3) trials. The cross-sections were ground, polished and etched with Nital 5% during 20 s. Micrographs and microhardness measurements were taken over three distinct regions of the wall: top, middle and bottom. A vertical line of equally spaced indentations (0.25 mm) was made with 0.1 kg load ($HV_{0.1}$) and 15 s of holding time in each region.

Fig. 4 Schematic of the measuring procedure based on the digital mesh of the walls used to quantify geometric features: (a) central region considered for measurement; (b) wall sides divided into equally spaced slices; (c) example of a region with an outlier layer highlighted in red

Additionally, chemical composition analysis was carried out on different samples with a fluorescence x-ray spectrometer (XRF—Olympus Vanta C series).

3 Results and discussions

3.1 Building of the reference working envelope

Figure 5 presents the surface aspect obtained for each of the twelve walls deposited to build the reference working envelope, using the experimental design shown in Table 2. For a same target wire feed speed (WFS_{target}) level, the conditions with slower actual travel speeds (TS_{actual}) presented poorer surface aspects (more irregularities). In this case, lower TS entails larger molten pool volumes for a same arc pressure (same current and arc length), making the weld pool more prone to lateral sagging and resulting in irregularities, corroborating the hypothesis proposed by Yehorov et al. [17]. Although lower levels of WFS (lower currents) prevent excessive arc pressure, higher levels can be used when combined with faster TS levels. Dirisu et al. [19], for example, managed to build walls with a WFS of 6.5 m/min and a

TS of 40.0 cm/min, also using the CMT process and the AWS ER70S-6 wire. However, it must be taken into account that this choice could result in a narrower TS working range since the arc pressure would be higher.

Table 3 presents the acquisition data from each wall deposited to build the reference working envelope. It is possible to notice that the average values of mean WFS (WFS_m) were similar for each target level, except when slower TS values were used (mainly with WFS of 5 m/min). Since walls with slower TS presented more irregular geometries, more significant variations in WFS were probably imposed by the CMT equipment to maintain constant arc length, resulting in the observed deviations. Mean current (I_m) and RMS current (I_{rms}) values were similar to those observed for WFS since both have a direct correlation. Moreover, mean and RMS voltage values (U_m and U_{rms} , respectively) remained at the same level for a given WFS_{target} , independently of the TS, showing the good performance of the synergy line in keeping arc length constant. The average values of mean arc energy per unit of length (E_m), in turn, varied mainly due to the wide variations adopted for TS, and on a minor scale due to the variations in average power for a given WFS.

Fig. 5 Surface aspects of the twelve walls deposited to build the reference working envelope according to Table 2, which attended the two acceptance criteria defined in Sect. 2.1

Table 3 Average values (out of 10 layers) of mean wire feed speed (WFS_m), mean current (I_m), RMS current (I_{rms}), mean voltage (U_m), RMS voltage (U_{rms}) and mean arc energy per unit of length (E_m) obtained for walls deposited to build the reference working envelope

Run	WFS_{target} (m/min)	TS_{actual} (cm/min)	WFS_m (A)	I_m (A)	I_{rms} (A)	U_m (V)	U_{rms} (V)	E_m (J/mm)
1	3	15.0	3.2 ± 0.2	123.8 ± 5.7	146.6 ± 7.0	11.4 ± 0.3	15.2 ± 0.2	766 ± 41
2	3	26.7	3.1 ± 0.2	119.3 ± 1.9	139.0 ± 2.5	11.4 ± 0.2	15.1 ± 0.2	395 ± 13
3	3	38.3	3.0 ± 0.2	120.6 ± 1.0	138.9 ± 1.2	11.5 ± 0.3	15.2 ± 0.3	280 ± 6
4	3	50.0	3.1 ± 0.2	121.0 ± 1.7	139.0 ± 2.1	11.6 ± 0.3	15.3 ± 0.3	216 ± 4
5	4	18.3	4.2 ± 0.4	147.2 ± 1.3	169.0 ± 1.0	12.4 ± 0.4	16.1 ± 0.4	753 ± 27
6	4	33.3	4.0 ± 0.4	146.1 ± 1.5	168.1 ± 1.2	12.3 ± 0.4	16.1 ± 0.4	413 ± 13
7	4	48.3	4.2 ± 0.2	148.7 ± 2.4	170.5 ± 2.1	12.6 ± 0.3	16.4 ± 0.2	298 ± 7
8	4	63.3	4.2 ± 0.2	146.6 ± 3.2	168.6 ± 2.8	12.6 ± 0.3	16.4 ± 0.3	226 ± 5
9	5	21.7	5.4 ± 0.4	177.5 ± 1.8	196.0 ± 1.7	13.4 ± 0.5	16.7 ± 0.4	733 ± 26
10	5	38.9	5.1 ± 0.2	171.3 ± 0.7	190.0 ± 0.6	13.4 ± 0.3	16.8 ± 0.3	403 ± 4
11	5	56.1	5.1 ± 0.2	170.5 ± 0.5	189.3 ± 0.4	13.4 ± 0.3	16.9 ± 0.2	287 ± 6
12	5	73.3	5.1 ± 0.2	169.4 ± 0.7	188.3 ± 0.6	13.5 ± 0.2	17.0 ± 0.2	220 ± 3

Table 4, in turn, presents the resultant geometrical features of the walls, namely, external wall width (WW_{ext}), effective wall width (WW_{eff}), layer height (LH) and surface waviness (SW). As seen, the standard deviations did not exceed 0.2 mm, indicating good reliability regardless of the geometric characteristic evaluated. Finally, Fig. 6a shows the working envelopes for WW_{ext} and WW_{eff} , whilst Fig. 6b presents the working envelope for LH, both with their respective mean values and iso- WFS_{target} curves. Analyzing Fig. 6a for a given WFS and TS, the effective wall widths are always less than the external wall widths. As the effective width is taken in the valleys established between two layers, a deviation between WW_{ext} and WW_{eff} was already expected. The size of these valleys depends on the dilution, which in welding is defined as the percentage of base metal that blends with the added material (wire) composition. In this condition, the effective width values would only approximate the external width value when the dilution between

the layers is such as to significantly reduce the formation of valleys in the side surface of the walls. Thus, in cases where dilution is low, more profound valleys tend to form, always leading to less effective widths than the external ones. As expected, Fig. 6b shows that the layer height decreases as TS is increased for the same WFS, since this variation reduces the amount of material deposited per unit of length. Nevertheless, when WFS is increased for a same TS, the opposite behaviour happens, leading to higher layer heights.

Surface waviness (SW) is another geometrical feature that can be adopted as a function of WFS and TS in a working envelope approach. Figure 7a presents the average values for SW and its fitting curves, whereas Fig. 7b shows a representation of the same data in the form of a 2D response surface made via a commercially available statistical analysis software package. A prediction equation (Eq. 1) was determined by the software to visually express the SW data as a contour plot. It is worth mentioning that the SW assessed

Table 4 Average values (taken from procedure illustrated in Fig. 4) of external wall width (WW_{ext}), effective wall width (WW_{eff}), layer height (LH), surface waviness (SW) for the walls of the reference working envelope (Table 2)

Run	WFS_{target} (m/min)	TS_{actual} (cm/min)	WW_{ext} (mm)	WW_{eff} (mm)	LH (mm)	SW (mm)
1	3	15.0	8.1 ± 0.1	6.6 ± 0.1	3.2 ± 0.0	0.8 ± 0.0
2	3	26.7	6.1 ± 0.0	4.9 ± 0.1	2.3 ± 0.0	0.6 ± 0.0
3	3	38.3	5.0 ± 0.1	4.0 ± 0.1	1.9 ± 0.0	0.5 ± 0.0
4	3	50.0	4.6 ± 0.1	3.5 ± 0.0	1.7 ± 0.0	0.5 ± 0.0
5	4	18.3	8.7 ± 0.1	6.8 ± 0.1	3.3 ± 0.0	1.0 ± 0.1
6	4	33.3	6.8 ± 0.0	5.1 ± 0.2	2.3 ± 0.0	0.9 ± 0.1
7	4	48.3	5.4 ± 0.0	3.9 ± 0.0	2.0 ± 0.0	0.8 ± 0.0
8	4	63.3	4.8 ± 0.1	3.4 ± 0.1	1.8 ± 0.0	0.7 ± 0.0
9	5	21.7	9.0 ± 0.2	6.6 ± 0.1	3.5 ± 0.1	1.2 ± 0.1
10	5	38.9	6.5 ± 0.1	4.9 ± 0.1	2.5 ± 0.0	0.8 ± 0.0
11	5	56.1	5.5 ± 0.1	4.1 ± 0.1	2.1 ± 0.0	0.7 ± 0.0
12	5	73.3	4.8 ± 0.1	3.3 ± 0.1	1.9 ± 0.0	0.8 ± 0.0

Fig. 6 Working envelopes as a function of the actual travel speed (TS) and target iso-wire feed speeds (WFS): (a) for the external wall width (WW_{ext}) and the effective wall width (WW_{eff}) and (b) for layer height (LH)

in this work does not include the formation of humps and considers only the surface finish in the side of the walls. One must remember that an operating range of travel speed was established to avoid such irregularities. By analyzing Fig. 7a, one can see that when the same level of WFS is considered, surface waviness tends to reduce with increasing TS. On the other hand, this behaviour is not straightforward for faster WFS, like 5 m/min. Since the differences obtained between a given test and its adjacent ones are minimal (only about 0.1 mm), the trends carry some degree of uncertainty, justifying the difference in waviness trends at the three WFS levels. However, in general, as it can be seen through the contour lines in Fig. 7b, greater waviness occurs for lower TS and higher WFS (larger molten pool volume and higher arc pressure), and a smoother surface for the other way around (smaller molten pool volume and low arc pressure), respecting the limits of TS for high and low WFS.

$$SW = -0.6952 - 0.0069xTS + 0.0003xTS^2 + 0.6817xWFS - 0.0404xWFS^2 - 0.0050xTSxWFS \quad (1)$$

$$(R^2 = 0.94; \text{adjusted}R^2 = 0.89)$$

3.2 Validation of the reference working envelope

Three walls were deposited with different combinations of WFS_{target} and TS aiming at a target effective width of 4.5 mm (arbitrarily chosen) to validate the reference working envelope. The values of WFS and TS (in the second and third columns in Table 5) were defined by interpolation within the reference working envelope (Fig. 6a) from the target effective wall width. As evidenced, none of the combinations coincided with those used to build the working

Fig. 7 Surface waviness (SW) (Table 4) as a function of the actual travel speed (TS) and target wire feed speed (WFS) (Table 3): (a) experimental data and fitting curves and (b) contour lines super-

imposed by the experimental data (note that extrapolations from the data that compose the envelope may increase uncertainties of the estimation)

Table 5 Selected wire feed speed (WFS_{target}) and actual travel speed (TS_{actual}) combinations and resultant predicted and measured geometric features for the validation trials

Wire	WFS_{target} (m/min)	TS_{actual} (cm/min)	Predicted values (mm)				Measured values (mm)			
			WW_{ext}	WW_{eff}	LH	SW	WW_{ext}	WW_{eff}	LH	SW
AWS ER70S-6	3.1	32.0	5.6	4.5	2.1	0.6	5.9 ± 0.0	4.5 ± 0.0	2.1 ± 0.0	0.7 ± 0.0
	3.8	38.5	6.0	4.5	2.1	0.7	5.7 ± 0.0	4.4 ± 0.1	2.2 ± 0.0	0.6 ± 0.0
	4.7	45.0	6.0	4.5	2.2	0.8	5.9 ± 0.1	4.6 ± 0.0	2.2 ± 0.0	0.7 ± 0.1

envelope (Table 2), a principle of validation approaches. All other parameters were kept the same as in the construction of the reference working envelope. The remaining columns of Table 5 show the predicted and measured external wall width (WW_{ext}), effective wall width (WW_{eff}), layer height (LH) and surface waviness (SW). The predicted WW_{ext} and LH were also reached by interpolation in the envelopes of Fig. 6a, b, respectively. The predicted SW was obtained by using Eq. (1). Table 6, in turn, contains the deviations between predicted and measured values. Within the geometric features assessed, WW_{ext} had the highest deviations between the measured and predicted values, varying at around ± 0.3 mm. All the other features presented deviations between ± 0.1 mm. These low deviations indicate the robustness of the working envelope approach (the fact that the deviations present no tendencies concerning being greater or less than the predicted values also suggests statistical reliability).

As shown in Fig. 8, the arc energies per unit of length calculated for Table 5 trials (in which different WFS and TS combinations reaching the same target effective width) were very similar (considering the standard deviations amongst layers). The wall geometries were practically the same (suggesting that the heat flow through the wall was similar). This behaviour was expected, since heat flux is the most important governing parameter to define the geometrical wall features. Accordingly, the thermal cycles experienced by the layers probably followed the same tendency (all facts indicating a strong correlation between arc energy and heat input). Consequently, no significant differences in microstructures were observed in the samples built in the validation trials, as shown in Fig. 9. However, it is well known that microstructure is governed by arc energy and thermal cycle and by chemical composition. In this sense, chemical composition analysis was carried out with a fluorescence x-ray spectrometer (XRF) to assess the possible influence of the deposition parameters over the burning losses of elements.

Table 6 Deviations between predicted and measured geometric features shown in Table 5

Wire	WFS_{target} (m/min)	TS_{actual} (cm/min)	Deviations (mm)			
			WW_{ext}	WW_{eff}	LH	SW
AWS ER70S-6	3.1	32.0	0.3	0.0	0.0	0.1
	3.8	38.5	−0.3	−0.1	0.1	0.0
	4.7	45.0	−0.1	0.1	0.0	−0.1

In phase with the previous results, Table 7 suggests no significant variations (or trends) when chemical compositions were quantified over the extreme WFS and TS conditions. One can also assume that no chemical variation occurred between the walls from the validation trials.

Naturally, microstructure changes were observed between the top layer and the remaining layers that underwent thermal retreatment from multiple thermal cycles. This behaviour was also observed by Aldalur et al. [20] and Kozamernik et al. [21] when using WAAM with the same ER70S-6 wire. To illustrate this behaviour, Fig. 10 presents macro and micrographs for the intermediate condition within the validation trials. As seen, no imperfections are observed. It can be noticed that the last deposited layer, which corresponds to a region not subject to reheat from the following layers (region 1), presents large columnar grains composed majorly by grain boundary ferrite (PF(G)) and acicular ferrite (AF). Region 2 illustrates that the fusion line is not easily perceived by optical microscope. Typical microconstituents of primary solidification zones are presented, such as grain boundary ferrite (PF(G)), acicular (AF), side plate ferrite (FS(A)) and some veins of polygonal ferrite (PF). Both the middle (region 3) and bottom regions of the wall (region 4) do not present major differences in microstructure between themselves and contain mainly polygonal ferrite. It can be said that these regions experience a similar thermal history based on the microstructure. However, it is worth noting that the microstructures of regions 1 and 2 occur only at the top surface of a thin wall and can be easily machined

Fig. 8 Arc energies per unit of length of the walls (with error bars) built for the validation trials (same target width with different combinations of WFS and TS)

Fig. 9 Typical microstructures at the building direction centre of the walls used for validation of the reference envelope (AWS ER70S-6): (a) WFS = 3.1 m/min and TS = 32.0 cm/min; (b) WFS = 3.8 m/min and TS = 38.5 cm/min; (c) WFS = 4.7 m/min and TS = 45.0 cm/min

out if it is the case. The principal volume of a wall will be composed of microstructures illustrated in regions 3 and 4, as long as the thermal management during the building keeps the same interlayer temperature. Notwithstanding, regions 1 and 2 turn to be relevant in short walls concerning mechanical functionality. This is the reason to present this microstructural feature in the current study.

Figure 11 presents the microhardness profiles from the validation trials. There is no significant variation of the mean hardness when the three parametric conditions are compared (coherent with the microstructural features), as presented in Fig. 12. The average microhardness at the multi heat-treated regions is around 185 HV, within a narrow range of between 170 and 200 HV. The top region, in turn, shows a broader variation (of between 170 and 245 HV) as a consequence of the different ferrite morphologies typical of primary solidification. As evidenced in Fig. 13, the higher microhardness values in the top region are associated with regions rich in acicular ferrite.

3.3 Exploring the potential of the working envelope approach for parameter transferability

Three walls were deposited to assess the transferability of parameters from an existing working envelope when changing the feedstock, now using a high strength low alloy steel wire (AWS ER90S-B3). The same parameter combinations

(columns 2 and 3 of Table 5) used for the reference envelope validation were replicated. Consequently, a similar estimated wall width as the walls for the reference envelope validation is expected at the outset. Thus, the following discussions are based on the comparison between the walls built for both transferability and validation of the reference envelope. In this context, Fig. 14 presents the appearance of the walls, in which no significant changes in the surface aspect are noticed when contrasting walls made with the same wire. However, more regular surfaces were achieved with the AWS ER90S-B3 wire when compared to AWS ER70S-3. It is also noticeable in this figure that WFS matches the target values for both wires, indicating that the walls were deposited with the same set of parameters.

Table 8 presents the predicted and measured geometric features, namely, external wall width (WW_{ext}), effective wall width (WW_{eff}), layer height (LH) and surface waviness (SW). Table 9 presents the deviations (measured values minus the predicted ones). It can be verified that the external wall widths were always narrower and heights taller than expected, a difference not so significant when effective width is taken into account. Surface waviness was always less than predicted, reaching deviations of up to -0.3 mm, quantifying the best surface finish observed for the builds with the AWS ER90S-B3 wire, shown in Fig. 14. Since there is a difference in chemical composition between both materials, divergences could be expected.

Table 7 Chemical composition (in weight %) for the extreme WFS and TS conditions of the reference working envelope

WFS _{target} (m/min)	TS _{actual} (cm/min)	Mn	Si	Cr	Mo	P	Ni	Cu	Fe
3	15.0	1.21	1.07	-	-	0.02	-	-	Bal.
3	50.0	1.22	1.03	-	-	0.01	-	0.02	Bal.
4	18.3	1.20	1.05	0.02	-	0.02	-	0.02	Bal.
4	63.3	1.23	1.07	0.02	-	-	-	0.03	Bal.
5	21.7	1.28	1.07	-	-	0.02	-	-	Bal.
5	73.3	1.23	1.06	-	-	-	-	0.02	Bal.

Due to the low atomic number, carbon cannot be quantified by this method (the marginal contents of Cu, Cr and P are probably impurities coming from the wire)

Fig. 10 Macro and micrographs, at the bottom (4), middle (3) and top regions (1) of a cross-section from the intermediate validation wall (WFS = 3.8 m/min and TS = 38.5 cm/min) deposited with AWS ER70S-6

To better understand how the physical properties of the molten pool could have changed between the wires, Table 10 presents the chemical compositions for both materials. These

correspond to the mean values shown in Table 7 for the AWS ER70S-6 wire and the mean values obtained for the walls deposited with the AWS ER90S-B3 wire, which will

Fig. 11 Microhardness profiles along the building direction of the walls used for validation of the reference envelope (AWS ER70S-6): (a) WFS = 3.1 m/min and TS = 32.0 cm/min (average and standard deviation per region: Bottom = 184.1 ± 7.9 HV; Middle = 190.5 ± 8.0 HV; Top = 203.8 ± 13.7 HV); (b) WFS = 3.8 m/min and TS

= 38.5 cm/min (average and standard deviation per region: Bottom = 184.1 ± 6.9 HV; Middle = 180.9 ± 8.0 HV; Top = 199.9 ± 19.9 HV); (c) WFS = 4.7 m/min and TS = 45.0 cm/min (average and standard deviation per region: Bottom = 179.0 ± 6.9 HV; Middle = 179.4 ± 16.5 HV; Top = 197.4 ± 16.5 HV)

Fig. 12 Representative average microhardness (excluding the wall top region of Fig. 11) and correspondent standard deviations from the walls built to validate the reference envelope (AWS ER70S-6)

be presented later (Table 11). Deng et al. [22] proposed Eq. (2) to estimate the dynamic viscosity (η) of liquid steels as a function of the chemical elements, where T corresponds to the temperature within an optimum range between 1463 and 1723 K. The authors verified that the dynamic viscosity increases as the Si and Ti contents are increased, whilst an inverse effect is caused by increasing contents of Mn, P and S. Thus, although AWS ER90S-B3 has a lower Si content compared to AWS ER70S-6 (0.40 wt% on average), which

would lead to a decrease in viscosity, the lower Mn content (0.72 wt%) would overcome this effect and cause the AWS ER90S-B3 molten pool to have a higher viscosity, resulting in higher resistance to movement induced by arc pressure and, as a consequence, the resultant bead would be narrower (wall width) and taller (layer height). It is worth mentioning that, as shown in the referred equation, Mn content has a higher coefficient when compared to Si content, indicating that Mn has a stronger effect over molten metal viscosity. Besides that, the existence of some surface-active agent (S, O, Se and Te), even in small amounts, could change wettability and lead to changes in molten pool geometry. For instance, Keene et al. [23] observed large variations in surface tension between 316 stainless steel grades with a difference of 139 ppm (0.0139%) of S. Finally, both viscosity and surface tension are highly dependent on temperature, so possible changes in thermal diffusivity between the materials may also affect the wall geometry.

$$\eta = 34.42973 - 0.01514 \cdot T - 0.00349 \cdot C + 0.76756 \cdot Si - 2.35139 \cdot Mn - 3.63856 \cdot P - 6.91921 \cdot S + 5.91118 \cdot Ti \quad (2)$$

To discuss the effect of the feedstock on arc physic aspects, Fig. 15 presents the average values from the main process parameters monitoring (mean and RMS current, mean and RMS voltage). Slightly higher mean and RMS current can be seen in the walls built with AWS ER90S-B3 (Fig. 15a, b), although the same WFS and TS had been set. This means that a higher current is needed to melt the AWS ER90S-B3 wire at the same melting rate. To investigate this behaviour, mean values of arcing time (t_{arc}) and short-circuiting time (t_{sc}) were calculated through the electric signal data from five layers, using a home-developed software (CURTOWELD), registered by Vilarinho and Araújo [24]. The synergy line of CMT imposed on these materials 50% of arcing and short-circuiting times, but with different durations. For the AWS ER70S-6 wire, t_{arc} and t_{sc} presented the same value equal to 6.3 ms, while with AWS ER90S-B3, they were equal to 6.0 ms. As a result, the short-circuiting frequency with ER90S-B3 (82.9 Hz) was slightly higher than with ER70S-6 (79.8 Hz). A slight increasing shifting between current and voltage waveforms from both wires can be seen in Fig. 16, due to the difference in short-circuiting frequency. As noticed in Fig. 16, the currents at arcing and short-circuiting times are similar to the two wires.

Short-circuit frequency by itself does not justify the higher current levels for AWS ER90S-B3 to maintain the same melting rate (same WFS). For this to happen, it would be necessary that the t_{arc}/t_{sc} ratio be greater for the low alloy steel wire, which does not occur. However, this current related behaviour can be discussed with the aid of the equation for melting rate in short-circuiting metal transfer

Fig. 13 Micrography indicating microhardness indentations and results at the top region of the validation wall built with WFS = 3.8 m/min and TS = 38.5 cm/min

Fig. 14 (a) Surface aspect of the validation walls (AWS ER70S-6) and transferability walls (AWS ER90S-B3); (b) Average wire feed speed obtained for the walls mentioned

(Eq. 3), detailed in Jorge et al. [25]. In this equation, MR is the melting rate, α and β are constants that depend on electrode polarity, shielding gas composition, wire material, ρ is the electric resistivity of the wire, L is the electrified wire free extension, S is the cross-section area of the wire, I_m is the mean current, I_{rms} the root mean square of current, t_{arc} is the arcing time and t_{sc} is the short-circuiting time.

$$MR = \left(\alpha I_m + \beta \frac{\rho L}{S} I_{rms}^2 \right) \Big|_0^{t_{arc}} + \left(\beta \frac{\rho L}{S} I_{rms}^2 \right) \Big|_{t_{arc}}^{t_{sc}} \quad (3)$$

Knowing that the same melting rate was achieved for a given combination of WFS and TS (Fig. 14b) and considering that the arc length was the same for both wires (intrinsic due to the use of the same synergic line), the higher current with AWS ER90S-B3 can be justified by the following hypothesis: a) cross-section area (S) wire is larger; b) a lower electrical resistivity (ρ); c) α and β values become lower. The first hypothesis was confirmed by measuring the wire diameters with a micrometer (seven measurements in each wire) and the results showed that the diameters were 1.17 ± 0.01 mm and 1.15 ± 0.0 mm, respectively, for AWS ER90S-B3 and AWS ER70S-6 (leading to areas of 4.30 e 4.15 mm²). One evidence that

could lead to the conclusion that the low alloy steel wire attains lower electrical resistivity (ρ) would come from the marginally lower mean and RMS voltages (Fig. 15c, d) when this wire was used. The third hypothesis, related to the constant α e β , was not possible to be assessed in this work. Whatever the reason or combination, it is demonstrated that the two wires had different arc physics properties, not only different chemical compositions. Hence, their use to demonstrate the potential of parameter transferability of the approach working envelope is assured.

Closing the analysis of the electrical signals, Fig. 17 demonstrates that, similar to the validation trials (Fig. 8), no significant difference amongst the arc energies per unit of length is observed amongst the 3 walls employed to achieve the same effective wall width (4.5 mm) with AWS ER90S-B3 as feedstock (considering the standard deviations). However, other combinations of WFS and TS might deliver different results. Therefore, it was not surprising that the wall geometries were practically the same, as seen in Tables 8 and 9. Furthermore, according to Table 11, no variation in the deposited chemical composition was observed either. As a consequence of the similarity between the results of arc energy, geometry and chemical composition,

Table 8 Selected wire feed speed (WFS_{target}) and actual travel speed (TS_{actual}) combinations and resultant predicted and measured geometric features for the transferability trials

Wire	WFS _{target} (m/min)	TS _{actual} (cm/min)	Predicted values (mm)				Measured values (mm)			
			WW _{ext}	WW _{eff}	LH	SW	WW _{ext}	WW _{eff}	LH	SW
AWS ER90S-B3	3.1	32.0	5.6	4.5	2.1	0.6	5.4 ± 0.1	4.5 ± 0.0	2.3 ± 0.0	0.5 ± 0.0
	3.8	38.5	6.0	4.5	2.1	0.7	5.4 ± 0.1	4.6 ± 0.0	2.3 ± 0.0	0.4 ± 0.1
	4.7	45.0	6.0	4.5	2.2	0.8	5.6 ± 0.1	4.6 ± 0.0	2.3 ± 0.0	0.5 ± 0.0

Table 9 Deviations between predicted and measured geometric features shown in Table 8

Wire	WFS _{target} (m/min)	TS _{actual} (cm/min)	Deviations (mm)			
			WW _{ext}	WW _{eff}	LH	SW
AWS ER90S-B3	3.1	32.0	−0.2	0.0	0.2	−0.1
	3.8	38.5	−0.6	0.1	0.2	−0.3
	4.7	45.0	−0.4	0.1	0.1	−0.3

no significant differences in microstructures were observed amongst the samples built in the transferability trials, as shown in Fig. 18.

The same analysis applied to the reference working envelope towards the variation of microstructure and hardness along the wall building direction was replicated to the trials with the AWS ER90S-B3 wire. The condition with WFS = 3.8 m/min and TS = 38.5 cm/min is taken as an example and macro and micrographs from this trial are shown in Fig. 19. As seen, no imperfections are observed. Contrasting with the walls made of C-Mn steel (AWS ER70S-6), no significant changes in macro and microstructure are noticed even between the top layer and the remaining layers. More significant formation of tempered martensite is possible in the transition between the last two layers deposited (region 2), the middle of the wall (region 3) and in the bottom (region 4) when compared to the top layer (region 1). This is reasonable since these regions are subject to reheating by deposition the following layers and could be tempered. However, to correctly affirm the above, a more thorough microstructure investigation should be carried out, which is out of this work context. In this case, it can be affirmed only that microstructure is composed mainly of martensite, tempered martensite and bainite, which is in accordance with the findings of Dirisu et al. [19] and Sharma and Shahi [26] for AWS ER90S-B3.

Microhardness values ranged within 270 and 420 HV for the AWS ER90S-B3 walls, as can be seen in Fig. 20. A cyclic behaviour, indicated by red arrows, was identified. Depending on the peak temperatures and cooling rates of the multiple thermal cycles experienced, each region may present a higher or lower formation of martensite/bainite and lead to the observed result. The average microhardness values were around 335 HV, as shown in Fig. 21 with the respective standard deviations. As a whole, there are differences in the metallurgical architecture between the walls

Table 10 Mean values of chemical composition (in weight %) for the walls deposited with the AWS ER70S-6 and AWS ER90S-B3 wires

Wire	Mn	Si	Cr	Mo	P	Ni	Cu	Fe
AWS ER70S-6	1.23	1.06	0.01	-	0.01	-	0.01	Bal.
AWS ER90S-B3	0.51	0.66	2.41	0.93	0.02	0.05	0.12	Bal.

due to its low atomic number, carbon cannot be quantified by this method

Table 11 Chemical composition (in weight %) for the walls deposited for the transferability assessment trials (AWS ER90S-B3)

WFS _{target} (m/min)	TS _{actual} (cm/min)	Mn	Si	Cr	Mo	P	Ni	Cu	Fe
3.1	32.0	0.50	0.68	2.41	0.92	0.02	0.05	0.13	Bal.
3.8	38.5	0.51	0.65	2.40	0.92	0.02	0.05	0.10	Bal.
4.7	45.0	0.53	0.64	2.42	0.94	0.02	0.05	0.13	Bal.

due to the low atomic number weight percentage of carbon cannot be quantified by this method

for the envelope validation and the walls for evaluating the parameter transportability because the feedstocks are different. But the transportability of the parameters showed to be feasible.

3.4 The use of the working envelope approach for parameter optimization

To investigate the complementary objective as to the possibility of optimizing parameter selection for a same target width, Fig. 22 presents the reference working envelope for effective wall width considering arc energy per unit of length (E), surface waviness (SW) and active deposition time (t_{ad}) as responses. It must be highlighted that active deposition times were determined considering a wall with 140 mm in length, with a total height of 40 mm. First, the number of necessary layers was found by dividing 40 mm by the layer heights achieved for each WFS and TS combination (Table 4). Next, the number of layers for each condition was multiplied by the wall length (140 mm), considering the distances travelled. These distances were finally divided by the travel speeds, resulting in active deposition times (not considering dwell times).

Second-order models, defined in Eq. (4), were used to plot the contour lines. Aiming at improving the variability proportion that can be quantified for each model (R^2), the significance level of each term of the model was evaluated through ANOVA and the less significant terms (p -values > 0.05) were discarded. Equations (5), (6) and (7) present the models used to develop the surfaces in Fig. 22 and their respective R^2 and adjusted R^2 . According to Montgomery [27], adjusted R^2 corresponds to a variation of R^2 that is adjusted to the model's size, that is, the number of factors. R^2 higher than 0.95 means that 95% of the data variability can be explained by the models. Figure 22 also displays the respective observed-by-predicted charts on the right side of each contour plots. These charts are helpful to detect misspecifications in the structural model. Ideally, values should lie roughly along a 45-degree line. Predictions that are outside the interval are denoted as outliers. A high proportion of

Fig. 15 Weld monitored parameters from the validation (AWS ER70S-6) and transferability (AWS ER90S-B3) walls with the same set parameters: (a) mean current; (b) RMS current; (c) mean voltage; (d) RMS voltage

outliers suggests misspecifications in the model. Moreover, the distribution of the observations should be symmetrical around to the corresponding predicted values.

$$f(x, y) = A + Bx + Cx^2 + Dy + Ey^2 + Fxy \quad (4)$$

where $f(x, y)$ is the predicted or expected value, i.e. the regression function of the independent variables “ x ” and “ y ” (which in this case correspond to travel speed and effective wall width); “ A ” corresponds to the intercept (predicted value when all of the independent variables are equal to zero); and “ B ”, “ C ”, “ D ”, “ E ” and “ F ” are the estimated regression coefficients.

$$E(J/mm) = -599.2388 + 8.3168xTS + 216.8446xWW_{eff} - 2.0407xTSxWW_{eff} \quad (5)$$

$$(R^2 = 0.99; \text{adjusted} - R^2 = 0.99)$$

$$SW(mm) = -0.9799 + 0.0041xTS + 0.2325xWW_{eff} + 0.0027xTSxWW_{eff} \quad (6)$$

$$(R^2 = 0.77; \text{adjusted} - R^2 = 0.69)$$

$$t_{ad}(min) = -15.5018 + 0.3199xTS + 10.9595xWW_{eff} - 0.8609xWW_{eff}^2 - 0.1250xTSxWW_{eff} \quad (7)$$

$$(R^2 = 0.97; \text{adjusted} - R^2 = 0.96)$$

Figure 22a suggests that variations in WFS and TS tend to slightly affect arc energy per unit of length for a given effective width, mainly when lower width values are considered. For instance, when using the prediction equation to determine the arc energy per unit of length (Eq. 5) for a WW_{eff} of 4.0 mm and considering TS at 40.0 and 57.0 cm/min (close to the envelope boundaries), the

Fig. 16 (a) Current and (b) voltage waveforms for same WFS (3.8 m/min) and TS (38.5 cm/min) when using the AWS ER70S-6 and AWS ER90S-B3 wires

Fig. 17 Arc energies per unit of length of the walls (with error bars) built for the transferability trials (same target width with different combinations of WFS and TS)

predicted values of E are equal to 274 and 277 J/mm, respectively, resulting in a difference (ΔE) of only 3 J/mm. On the other hand, when a wall width of 6.5 mm is admitted, and considering TS at 16.0 and 22.0 cm/min (again close to the envelope boundaries), the predicted values of E are 731 and 701 J/mm, respectively, resulting in a ΔE of 30 J/mm. As already evidenced, variations in E between 339 and 348 J/mm ($\Delta E = 9$ J/mm) for AWS ER70S-6 (Fig. 8) and between 344 and 347 J/mm ($\Delta E = 3$ J/mm) for AWS ER90S-B3 (Fig. 17) were not enough to significantly change microstructure or microhardness profiles for a target width of 4.5 mm. Although this difference can become larger for higher widths, it is still unlikely that they are sufficient to lead to significant changes in microstructure and mechanical properties. Hence, for the reference working envelope, or a potential working envelope (AWS ER70S-6) considering the transferability to AWS ER90S-B3, it can be stated that, for a given target width, variations in WFS and TS do not significantly affect microstructure and microhardness.

Figure 22b shows that employing lower values of WFS and TS results in smaller SW and, consequently, better

surface finishing for a same effective wall width. Considering Eq. (6) and taking, for instance, 4.0 mm as WW_{eff} and values of TS equal to 40.0 and 57.0 cm/min (values close to the envelope boundaries), the resulting SW are 0.5 and 0.8 mm, respectively, resulting in a difference (ΔSW) of 0.3 mm. If a WW_{eff} of 6.5 mm is taken, with TS values of 16.0 and 22.0 cm/min (again close to the envelope boundaries) the resultant SW will be 0.9 and 1.0 mm, respectively, resulting in a ΔSW of 0.1 mm. This means that for larger widths, the surface finish deteriorates. However, it is less affected by the WFS/TS combination. It is important to draw attention to the fact that the low adjusted R^2 of Eq. (6) may become feasible if the correspondent contour plot represents this quantity. The observed-by-predicted chart for SW shows that the values lie reasonably along a 45-degree line and that the deviations are lower than 15%. Moreover, the distribution of the observations is symmetrical around the corresponding predicted values. All of this gives statistical confidence to the estimator, even with a relatively low adjusted correlation coefficient.

Finally, Fig. 22c indicates that by employing higher values of WFS and TS, for a given target width, active deposition time (t_{ad}) becomes shorter. Elapse times may be in the opposite direction at first sight. However, the reader must remember that for this material and power source, arc energy presents low changes for a given wall width (elapse time is roughly proportional to arc energy). Changes in the desired width also influence the deposition times found for different WFS and TS combinations. Based on Eq. (7), taking WW_{eff} as 4.0 mm and TS at 40.0 and 57.0 cm/min, the resulting t_{ad} are 7.4 and 4.3 minutes, respectively, resulting in a difference (Δt_{ad}) of 3.1 min. When the WW_{eff} of 6.5 mm is taken, with TS varying from 16.0 to 22.0 cm/min, the resulting t_{ad} are 11.5 and 8.5 min, respectively, resulting in a Δt_{ad} of 3.0 min. Although the t_{ad} does not take dwell times (necessary to reach the interlayer temperatures of 30 °C) into

Fig. 18 Typical microstructures at the building direction centre of the walls used for parameter transferability (ER90S-B3): (a) WFS = 3.1 m/min and TS = 32.0 cm/min; (b) WFS = 3.8 m/min and TS = 38.5 cm/min; (c) WFS = 4.7 m/min and TS = 45.0 cm/min

Fig. 19 Macro and micrographs, at the bottom (4), middle (3) and top regions (1) of a cross-section from the intermediate transferability wall (WFS = 3.8 m/min and TS = 38.5 cm/min) deposited with AWS ER90S-B3

consideration, the deposition times can be considered proportional to the total construction time if a same target width is admitted.

In summary, the approach applied in this work to optimize parameter selection allowed not only for visualization of the effects of each parameter over operational

Fig. 20 Microhardness profiles along the building direction of the validation step walls (AWS ER90S-B3): (a) WFS = 3.1 m/min and TS = 32.0 cm/min (average and standard deviation per region: Bottom = 329.3 ± 33.2 HV; Middle = 340.7 ± 38.9 HV; Top = 356.6 ± 44.6 HV); (b) WFS = 3.7 m/min and TS = 38.5 cm/min (average

and standard deviation per region: Bottom = 341.1 ± 40.0 HV; Middle = 336.8 ± 40.3 HV; Top = 350.1 ± 36.4 HV); (c) WFS = 4.7 m/min and TS = 45.0 cm/min (average and standard deviation per region: Bottom = 326.7 ± 41.6 HV; Middle = 322.1 ± 32.1 HV; Top = 329.4 ± 21.7 HV)

Fig. 21 Representative average microhardness (excluding the wall top region of Fig. 20) and correspondent standard deviations from the walls built to assess the parameter transferability (AWS ER90S-B3)

features desired for a same effective width, but also a quantification through equations. Computational optimization routines could be used to generate the optimum combination between TS and WFS for a desired wall width using arc energy, surface waviness, active deposition time and others, as an objective function or as restrictors. For instance, one could wish to find TS and WFS to build a wall with a determined width to provide at the same time the shortest active time, with a minimum surface waviness and with arc energy higher than a given value. Nevertheless, it must be highlighted that the interactions here discussed cannot be stated straightforward for working envelopes using other processes or materials. However, they worked well between the two materials evaluated.

Fig. 22 Reference working envelope for effective wall width considering the results for (a) arc energy per unit of length, (b) surface waviness and (c) active deposition time, as responses

4 Conclusions

This work was motivated by making the working envelope approach for WAAM parameterization more cost-effective and functional. The objective of this work was to verify the possibility of parameterizing thin walls based on a pre-existing working envelope, followed by investigating whether the approach can be used to optimize parameter selection. Based on these objectives and results, it can be concluded that:

- It is possible to select parameters for thin walls deposited through WAAM with a lower number of experiments, using a pre-existent working envelope for another ordinary material (parameter transferability), implying lower time and resource consumption before the deposition of a final component. However, it is essential to mention that deviations between predicted and measure values for different materials are highly dependent on the feedstock compatibility in terms of the physical-chemical properties of both materials. Thus, not every parameterization with other materials (different classes), using this approach will be necessarily successful without some degree of adaptation.
- The working envelope combined with contour lines also demonstrated to be an easy means of visualizing the effect of the primary process variables (travel speed and wire feed speed). Optimization for different objective functions and restrictors can be implemented in the working envelope approach, either manually or using computational resources.

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Availability of data and material The datasets used or analysed during this research are available from the corresponding author on reasonable request.

Declarations

Ethical approval The manuscript is all original, i.e. none of these parts has been published before, and it is not has been submitted for publication anywhere else.

Consent to participate Consent to participate was obtained from all individual participants included in the study.

Consent to publish Consent to publish was obtained from all individual participants included in the study.

Competing interests There are no conflicts of interest to disclose.

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