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Influence of Emissivity Calibration on Thermal History and Process–Property Relationships in Arc-Based Directed Energy Deposition

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ABSTRACT

Infrared thermography is increasingly used for thermal monitoring and control in Directed Energy Deposition using arc-based heat sources (DED-Arc). Although the emissivity values required for quantitative temperature measurements are often assumed constant. The extent to which this assumption propagates into process-relevant thermal descriptors and subsequent process–property correlations remains insufficiently quantified. This study investigates in-situ emissivity calibration for DED-Arc and evaluates the effect of interpass temperature control on the mechanical properties of ER70S-6 carbon steel walls. Three interpass control conditions were examined at a fixed maximum interpass temperature 150 °C and 250 °C, and a fixed interpass time of 30 s. Correlating thermographic data with embedded thermocouples revealed a systematic temperature dependence of emissivity, which was modelled using a second-order polynomial to reduce the mean absolute temperature measurement error to 3.73%. A sensitivity analysis was performed to quantify how incorrect emissivity assumptions may distort the reconstructed thermal cycles and bias the interpretation of process-property relationships. Applying this dynamic calibration enabled the accurate extraction of thermal histories and $\Delta t_{8/5}$ cooling times. The 150 °C and 250 °C conditions maintained stable quasi-steady thermal cycles, yielding $\Delta t_{8/5}$ values of 22.1 s and 26.6 s, respectively. The 30 s strategy induced severe heat accumulation, pushing interpass temperatures to roughly 730 °C. These thermal variations governed mechanical performance. The 150 °C and 250 °C strategies produced superior and comparable mechanical properties, with ultimate tensile strengths of approximately 515 MPa. In contrast, the severe heat accumulation in the 30 s condition significantly reduced ultimate strength to 470 MPa.

Keywords: DED-Arc, WAAM, Infrared thermography, Emissivity, Interpass temperature, Mechanical properties

1 Introduction

Directed Energy Deposition using arc-based heat sources (DED-Arc), widely known as Wire Arc Additive Manufacturing (WAAM), has become an important manufacturing route for the production of medium to large-scale metallic components due to its high deposition rate, reduced material cost, and broad alloy applicability [1–3]. These advantages make DED-Arc particularly attractive for structural and industrial applications in which productivity and scalability are critical. Despite this potential, the process remains highly sensitive to thermal conditions developed during deposition, since successive layer addition promotes substantial heat accumulation within the component [4–6]. As the build height increases, the thermal field evolves continuously, altering local cooling rates and, consequently, affecting surface quality, residual stress development, phase transformation behaviour, and the microstructure of the deposited material [7,8].

The control of interpass temperature is therefore a central issue in DED-Arc. Previous studies have shown that regulating the thermal state between successive layers, either by adjusting dwell times or by introducing active cooling strategies, can reduce excessive grain growth, limit anisotropic responses, and suppress the formation of undesirable microstructural constituents [9–11]. However, excessively conservative cooling strategies may significantly increase production time while offering only limited gains in part quality or mechanical performance [5,12]. For this reason, thermal management in DED-Arc must be understood not only as a quality-control problem, but also as a productivity constraint requiring a balanced and quantitative approach.

To describe the thermal history imposed during deposition, parameters such as peak temperature, cooling rate, and the $\Delta t_{8/5}$ interval, defined as the time required for the material to cool from 800 °C to 500 °C, are commonly used. The latter, is particularly relevant in steels because it is closely associated with phase transformation kinetics and the resulting microstructure [5,13,14]. Accurate determination of these descriptors is essential for predicting whether the material will evolve toward harder constituents, such as martensite, or toward softer transformation products, such as bainite or ferrite, with direct implications for strength, ductility, and toughness [12–15]. In this context, uncertainty in temperature measurement becomes especially critical, since errors in recorded thermal cycles or emissivity calibration may propagate into substantial deviations in calculated $\Delta t_{8/5}$ values and compromise the reliability of process control.

Temperature monitoring in DED-Arc systems may be performed using either contact-based or non-contact techniques [8,16]. Thermocouples remain one of the most reliable solutions for local temperature measurement because they provide direct point-wise data and can be easily calibrated. Nevertheless, their use in DED-Arc is constrained by intrusive installation, limited spatial coverage, and practical difficulties associated with dynamic deposition environments. In contrast, non-contact methods such as pyrometry and infrared thermography allow thermal monitoring without interfering with the process and can provide either point-based or full-field information. One of their main limitations lies in their dependence on surface emissivity, which is particularly problematic in metallic additive manufacturing, where oxidation, surface roughness, temperature evolution, and alloy chemistry may all influence radiative behaviour [17].

Several strategies have been proposed to address emissivity uncertainty. A common approach consists of direct comparison between infrared measurements and thermocouple data at selected locations, allowing empirical calibration under specific processing conditions [18]. Alternative approaches include the use of blackbody references for system-level calibration [19], dual-wavelength or two-colour pyrometry to reduce emissivity sensitivity [20], and more advanced multispectral imaging methods capable of separating temperature and emissivity on a pixel-wise basis [21]. Reported emissivity values in steel vary considerably, ranging from approximately 0.2–0.25 for relatively clean steel surfaces to values near 0.7 for oxidized mild steels at elevated temperature [9,17,22]. More specifically, constant emissivity values adopted in the DED-Arc literature include 0.84 for Q235 low-carbon steel and ER110S-G HSLA steel [5], 0.65 for carbon steel walls and lattice structures [9], 0.60 for deposited stainless steel [23], and 0.45 for low-carbon steel based on data reported above the melting point [24]. This wide dispersion highlights the difficulty of selecting a single representative emissivity for thermographic monitoring of steel DED-Arc processes.

Although substantial progress has been made in understanding the role of interpass temperature in determining microstructural evolution and mechanical performance in DED-Arc, uncertainty remains regarding the emissivity values adopted for thermographic monitoring of carbon steel deposition. The broad range of emissivity assumptions reported in the literature limits the comparability of thermal data and introduces uncertainty into process-relevant descriptors. More importantly, the extent to which emissivity uncertainty propagates into parameters such as interpass temperature and $\Delta t_{8/5}$, and consequently affects the interpretation of process–property relationships,

remains insufficiently quantified. This constitutes the main knowledge gap addressed in the present work.

The present study addresses this gap through in-situ emissivity calibration combining infrared thermography and thermocouple measurements for carbon steel DED-Arc under temperature- and time-based interpass control strategies. The novelty lies in quantifying how emissivity uncertainty propagates from temperature measurement into process-relevant thermal descriptors and, subsequently, into the interpretation of material response. A sensitivity analysis is used to assess the effect of uncalibrated emissivity assumptions on the reconstructed thermal history, while the calibrated thermal data are correlated with microstructure, microhardness, and tensile behaviour. This approach provides a more robust basis for quantitative thermographic monitoring and for establishing reliable process–thermal history–property relationships in DED-Arc.

2 Experimental procedure

2.1 DED-Arc system and materials

The experimental samples were manufactured using a robotic DED-Arc system consisting of an ABB IRB 4600 six-axis industrial robot integrated with a Fronius TPS 400i welding power source. The feedstock material was a 1.2 mm diameter Böhler AM46 solid carbon steel wire, corresponding to ER70S-6 classification [25]. Deposition was performed onto S460ML structural steel substrate plates [26], selected to ensure adequate mechanical compatibility and to minimise compositional mismatch between the substrate and the deposited material. The nominal chemical compositions of both the feedstock and substrate, as provided by the manufacturers, are listed in Table 1, while their nominal mechanical properties are summarised in Table 2. An 82% Ar + 18% CO₂ gas mixture was utilised for shielding and arc stabilisation. All builds were produced using a current of 150 A, a travel speed of 6 mm/s and pulsed metal transfer mode. To reduce geometric irregularities, particularly those associated with start and stop regions, the deposition direction was alternated between successive layers.

Table 1 – Chemical composition of the welding wire and substrate material (wt.%).

	C	Mn	Si	S	P	Cr	Mo	Ni	Fe
S460 ML	0.09	1.60	0.49	0.0006	0.012	0.041	0.008	0.032	Balance
ER70S-6	0.10	1.70	1.00	-	-	-	-	-	Balance

Table 2 – Nominal mechanical properties of the welding wire and substrate material.

Feedstock wire	Yield stress (MPa)	Ultimate strength (MPa)	Elongation at fracture (%)
ER70S-6	480	580	24
S460 ML	490	584	26

The experimental campaign was designed to assess the influence of thermal management on both the measured thermal cycles and the resulting tensile properties of the deposited material. Three carbon steel walls, each with nominal dimensions of 200 mm in length and 120 mm in height, were produced to isolate the effect of the interpass control strategy on the thermal history and subsequent material response. The experimental programme included three distinct deposition conditions, comprising two temperature-controlled regimes and one time-controlled regime. In the first and second conditions, maximum interpass-temperature thresholds of 150 °C and 250 °C were prescribed, respectively. In both cases, deposition of the subsequent layer was initiated only after the measured temperature had decreased to the corresponding threshold. In the third condition, a fixed dwell time of 30 s was imposed between successive layers, irrespective of the thermal state of the component. For the temperature-controlled walls, deposition of each subsequent layer was governed by closed-loop thermal feedback based on the maximum global temperature recorded by the infrared camera, such that the process was interrupted after each pass and only resumed once the measured temperature decreased to the predefined threshold. The full experimental matrix is summarised in Table 3. For clarity, the three deposition conditions are hereafter designated as W150, W250, and W30s, corresponding respectively to interpass control at 150 °C, interpass control at 250 °C, and a fixed interpass dwell time of 30 s.

Table 3 – Summary of the DED-Arc deposition conditions and interpass control strategies adopted for the fabrication of the carbon steel walls.

Wall ID	Interpass condition	Current (A)	Voltage (V)	Travel speed (mm/s)	Shielding gas
W150	150 °C	150	21.3	6	82% Ar + 18% CO ₂
W250	250 °C				
W30s	30 s				

2.2 Thermal monitoring

To capture the transient thermal evolution during deposition and to determine cooling-related parameters such as $\Delta t_{8/5}$, thermal monitoring was performed using both an infrared camera and thermocouples. The global thermal field was recorded using a

FLIR A655sc infrared camera with a resolution of 640×480 pixels. The camera was positioned at an approximate distance of 500 mm from the substrate, providing a field of view with a width of 415 mm, which corresponded to a spatial resolution of approximately 0.65 mm per pixel. The recorded thermographic data were subsequently processed using FLIR Thermal Studio software for spatial and temporal analysis.

Local thermal validation was performed using four embedded Type-K thermocouples positioned along the wall height near one edge, as illustrated in Figure 1. The thermocouples were vertically spaced at intervals of 20 mm to capture the temperature evolution at different locations throughout the deposited wall. Temperature data were acquired using an HBM QuantumX MX1609 amplifier coupled with Catman software. To reduce the risk of thermocouple detachment caused by remelting during subsequent deposition passes, the sensors were fixed by capacitive discharge spot welding approximately 5 mm below the top surface of the previously deposited material during the build sequence.

For calibration of the thermographic measurements, specific measurement points were manually defined during data export in FLIR Thermal Studio at locations corresponding to the visible thermocouple positions on the thermal images (Figure 1c). This enabled direct point-by-point comparison between the temperature histories obtained from the infrared camera and those measured by the corresponding thermocouples. The emissivity value adopted in the thermographic analysis was then progressively adjusted until the discrepancy between both datasets was minimised and the closest possible agreement between the corresponding temperature-time curves was achieved.

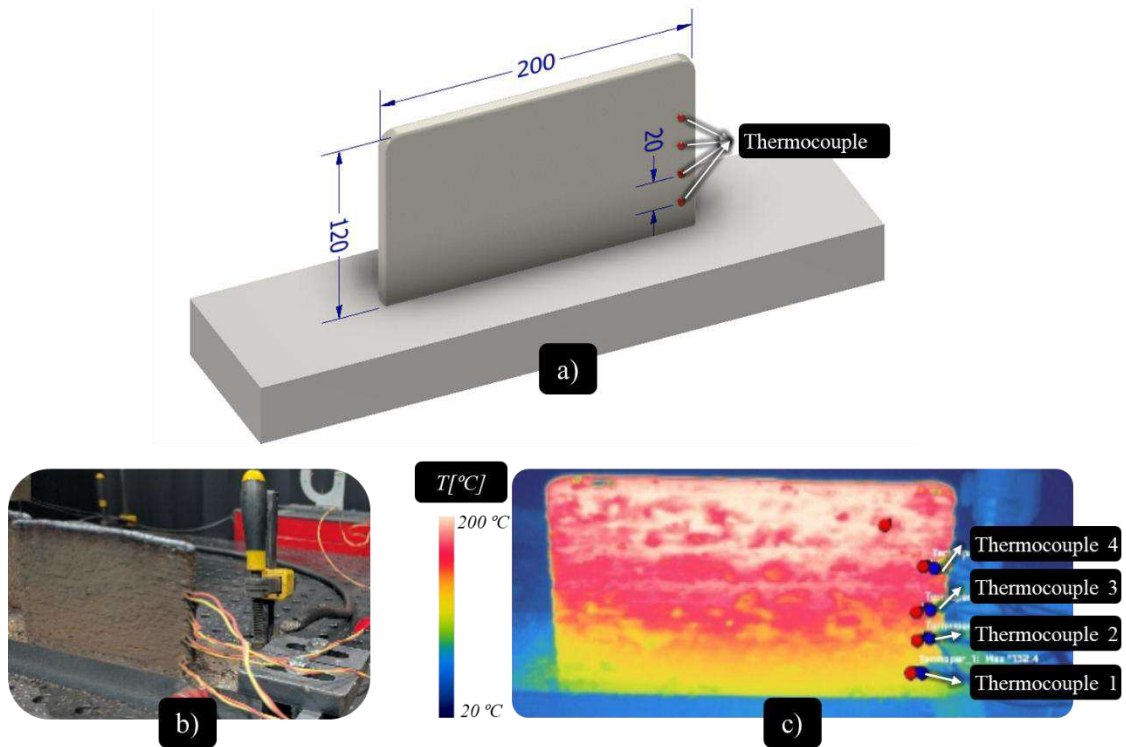


Figure 1 – Thermal monitoring setup used during DED-Arc deposition: (a) schematic representation of the wall geometry and thermocouple locations, (b) experimental view of the deposited wall with embedded thermocouples, and (c) representative infrared image showing the monitored wall and the corresponding thermocouple measurement points.

2.3 Microstructural and mechanical characterisation

Following deposition, rectangular metallographic samples with nominal dimensions of $25 \times 10 \times 5 \text{ mm}^3$ were extracted transversely from each wall at the locations indicated in Figure 2a. The samples were cold-mounted, ground and polished following standard metallographic preparation procedures, and subsequently etched with a 2% Nital solution to reveal the microstructural features. Optical microscopy was performed using a Leica DM4000 M LED microscope. The acquired micrographs were used to assess the grain morphology and to quantify the equivalent grain-size distribution under the different interpass conditions.

Vickers microhardness measurements were performed on the same metallographic samples using a Wilson VH1102/1202 microhardness tester under an applied load of 0.5 kgf. Indentations were placed at 0.5 mm intervals along vertical traverses parallel to the build direction and along horizontal traverses across the wall thickness. This measurement arrangement enabled the evaluation of local hardness

variations associated with the layer-by-layer deposition sequence, the repeated thermal cycles and the different interpass control strategies.

The global mechanical response of the deposited material was evaluated by means of uniaxial tensile testing. Flat tensile specimens were extracted horizontally from the deposited walls, as illustrated in Figure 2a, and machined to the geometry presented in Figure 2b. The characteristic surface waviness of the as-built walls was removed during machining, thereby minimising the influence of geometric imperfections and enabling the intrinsic mechanical properties of the deposited material to be assessed. Only horizontally extracted specimens were considered, since several studies on carbon steel WAAM components have reported limited mechanical anisotropy under comparable processing conditions [27–29]. For each wall, three specimens were extracted and tested in accordance with ISO 6892-1:2019 [28].

The uniaxial tensile tests were carried out using a 250 kN Shimadzu AGX-250KNV2 CE electromechanical universal testing machine. Axial strain was measured using a mechanical extensometer manufactured by MFA Mess- & Feinwerktechnik GmbH. In addition to the conventional extensometer, the tests were coupled with three-dimensional digital image correlation (DIC) using the ISTR4 4D system [30], allowing full-field strain measurement and a more detailed assessment of local deformation behaviour during tensile loading.

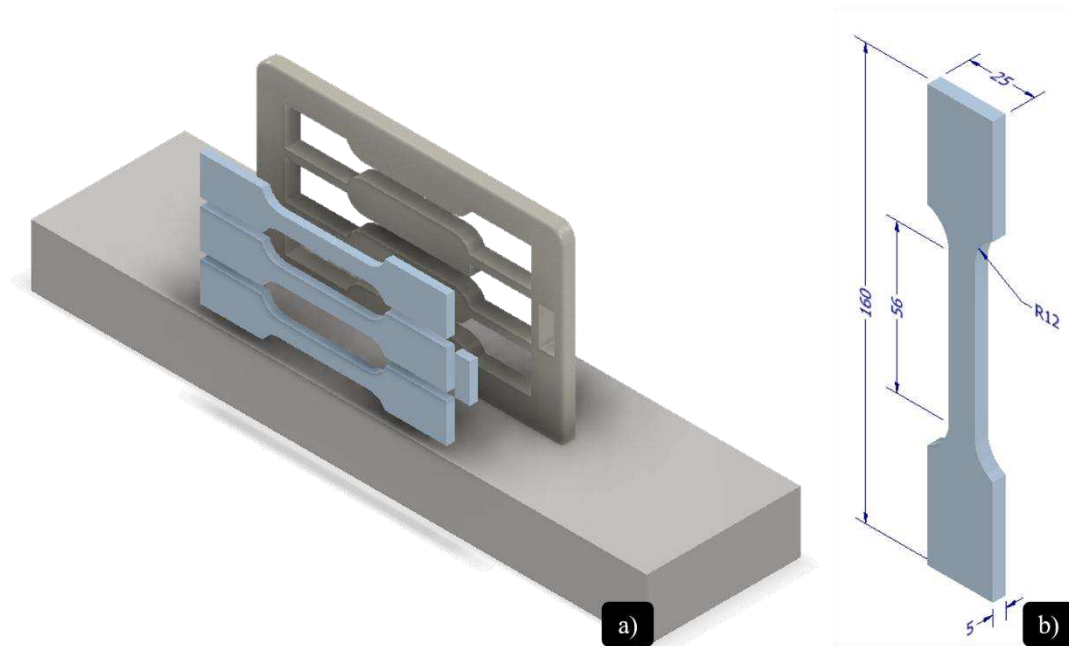


Figure 2 – Schematic representation of (a) the extraction locations of the tensile specimens and transverse metallographic samples from the deposited wall, and (b) the geometry and dimensions of the flat tensile specimen. The metallographic samples had nominal dimensions of $25 \times 10 \times 5 \text{ mm}^3$.

3 Results and discussion

3.1 In-situ emissivity calibration and validation

To accurately monitor the thermal history during the DED-Arc process, an in-situ emissivity calibration was performed by correlating infrared thermography data with embedded thermocouple measurements. Figure 3a to c show the temporal evolution of temperatures over the first 1000 seconds following the welding of thermocouple 3 (Figure 1) for the W150, W250, and W30s samples. The data compares the reference thermocouple measurements against the thermographic readings calculated at fixed emissivity (ε) bounds of $\varepsilon = 0.5$ and $\varepsilon = 0.9$.

The transient thermal fields exhibit distinct heating and cooling phases corresponding to the torch passes over the thermocouple location. For all conditions, peak temperatures are highest at the onset of monitoring and progressively decay as the layer height increases, thereby distancing the heat source from the sensor. The influence of the interpass dwell time is highly evident in the frequency of the thermal cycles. The W150 strategy exhibits fewer thermal cycles within the initial 1000 s window due to the prolonged cooling periods required to reach the 150°C interpass threshold. Conversely, the fixed 30 s interpass time results in rapid successive depositions, leading to heat accumulation and significantly higher localized temperatures. Additionally, the bidirectional deposition strategy (alternating travel directions between layers) resulted in paired thermal peaks, reflecting the variable temporal spacing of the torch relative to the thermocouple.

The comparison between thermocouple and thermographic measurements also highlights the strong influence of emissivity on the temperature estimated by the infrared camera. For all conditions, the thermocouple curve lies between the two thermographic curves obtained with $\varepsilon = 0.5$ and $\varepsilon = 0.9$, indicating that neither of these arbitrary emissivity values provides a fully accurate representation of the true temperature history. This trend is particularly evident in the W30s wall, for which the discrepancy between the thermocouple signal and the thermographic curves becomes more pronounced at higher temperatures. This behaviour can be explained by the Stefan–Boltzmann law, which states that the emitted radiative energy is proportional to εT^4 [19], where T represents the temperature measured. Consequently, the temperature measured by infrared thermography is highly sensitive to the emissivity assigned in the analysis, and

this sensitivity becomes more pronounced at higher temperatures due to the nonlinear increase in radiative emission.

To quantify the uncertainty associated with emissivity selection, Figure 3d to f presents the average error between the thermocouple temperature and the temperature measured by the infrared camera for a range of constant emissivity values between 0.3 and 1.0. In all three walls, a well-defined minimum error is observed, confirming that an optimum emissivity can be identified experimentally for each deposition condition. For W150 and W250, the minimum average errors were obtained for $\varepsilon=0.71$, resulting in deviations of 5.35% and 3.44%, respectively. For W30s, the optimum emissivity shifted slightly to $\varepsilon=0.76$, yielding the lowest average error of 1.76%. These results indicate that the emissivity was not strictly constant across all process conditions. Such variation may be attributed to the combined influence of surface temperature, oxidation state, and local surface condition during deposition [31]. Under faster deposition and stronger thermal accumulation, as in W30s, the surface remained at higher temperature for longer periods, which likely promoted more stable oxide formation and altered the radiative behaviour of the deposited material.

Although the optimum emissivity differed slightly between conditions, the calibrated thermographic results showed good agreement with the thermocouple data in all cases, with average errors remaining below 6%. By contrast, the use of non-calibrated emissivity values can introduce very large temperature errors, up to approximately 80% for unfavourable emissivity assumptions.

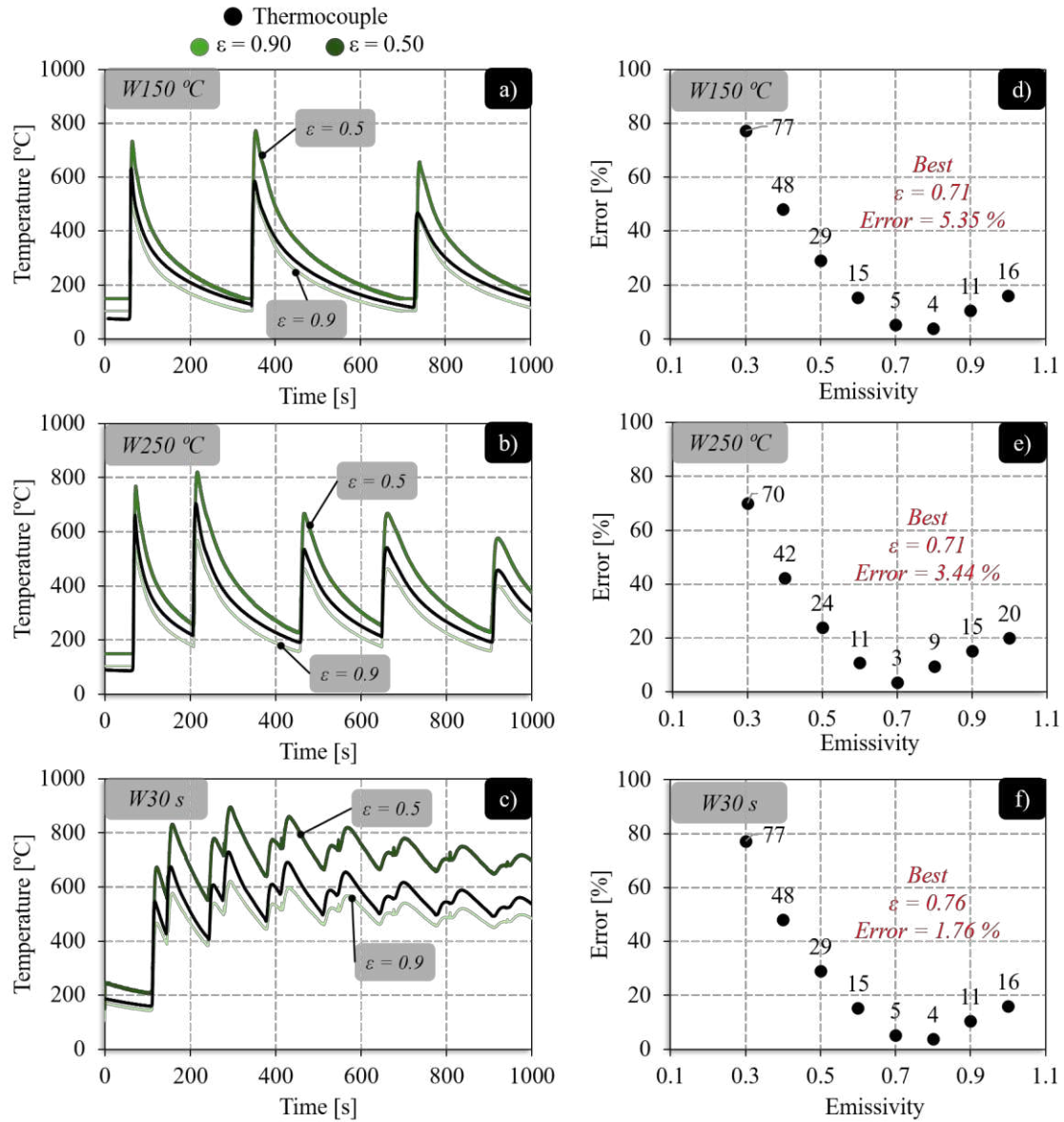


Figure 3 –In-situ emissivity calibration. (a–c) Thermal profiles during the first 1000 s for W150, W250, and W30s walls, comparing thermocouple measurements with infrared thermography at fixed emissivity ($\epsilon = 0.5$ and $\epsilon = 0.9$). (d–f) Mean absolute error between thermocouple and infrared measurements, identifying the optimal emissivity for each deposition strategy.

To further refine the thermal monitoring accuracy, the instantaneous temperature-dependent emissivity was evaluated. Figure 4 illustrates the evolution of the calculated emissivity as a function of temperature for the W150, W250, and W30s deposition strategies. For all walls, only temperature data acquired during the cooling stages were considered. This choice was made to minimize possible disturbances associated with arc radiation, shielding gas and local reflections during deposition, which can affect infrared measurements taken during the heating stage. In addition, from a metallurgical point of view, the cooling phase is the most relevant for the analysis of solid-state transformations

in steel, particularly in relation to thermal descriptors such as $\Delta t_{8/5}$. The colour scale in Figure 4 represents the acquisition time for each wall. For each data point, the instantaneous emissivity was dynamically adjusted so that the thermographic reading matched the reference thermocouple measurement.

The results show that, despite some scatter, all three walls exhibit a consistent evolution of emissivity with temperature. In general, emissivity tends to increase from lower temperatures up to an intermediate range, after which a slight stabilisation is observed at higher temperatures. Although some dispersion is visible, particularly at earlier deposition times, the overall overlap between the datasets indicates that the emissivity behaviour is reasonably repeatable across the different deposition strategies. Consequently, a global second-order polynomial regression was fitted to the experimental data to establish a continuous, temperature-dependent emissivity function:

$$\varepsilon(T) = 0.51 + 9.77 \times 10^{-4}T - 9.77 \times 10^{-7}T^2 \quad (1)$$

where T is the temperature in °C. Although the fit shows moderate dispersion ($R^2=0.5$) it captures the overall trend of the experimental data and provides a practical means of estimating emissivity as a function of temperature. Importantly, the measurements cover a temperature range of approximately 150 to 750 °C, which encompasses the range of greatest relevance for the present study. This includes not only the interpass temperatures investigated, but also the temperature interval associated with the $\Delta t_{8/5}$.

To validate the effectiveness of the dynamic model, Table 4 compares the mean absolute temperature measurement errors obtained using the previously identified constant emissivities ($\varepsilon = 0.71$ and $\varepsilon = 0.76$) with those obtained using the proposed temperature-dependent function (Eq. 1). All three approaches provided good agreement with the thermocouple measurements, with average errors below 6%. In particular, a constant emissivity of $\varepsilon = 0.71$ already provided satisfactory accuracy across the three deposition conditions, with an overall mean error of 4.66%. Nevertheless, the temperature-dependent formulation yielded the lowest overall mean error, reducing it to 3.73%. Although the improvement in average accuracy was moderate, the proposed formulation additionally accounts for the experimentally observed variation of emissivity with temperature and provides a unified approach for thermographic analysis across the different deposition conditions.

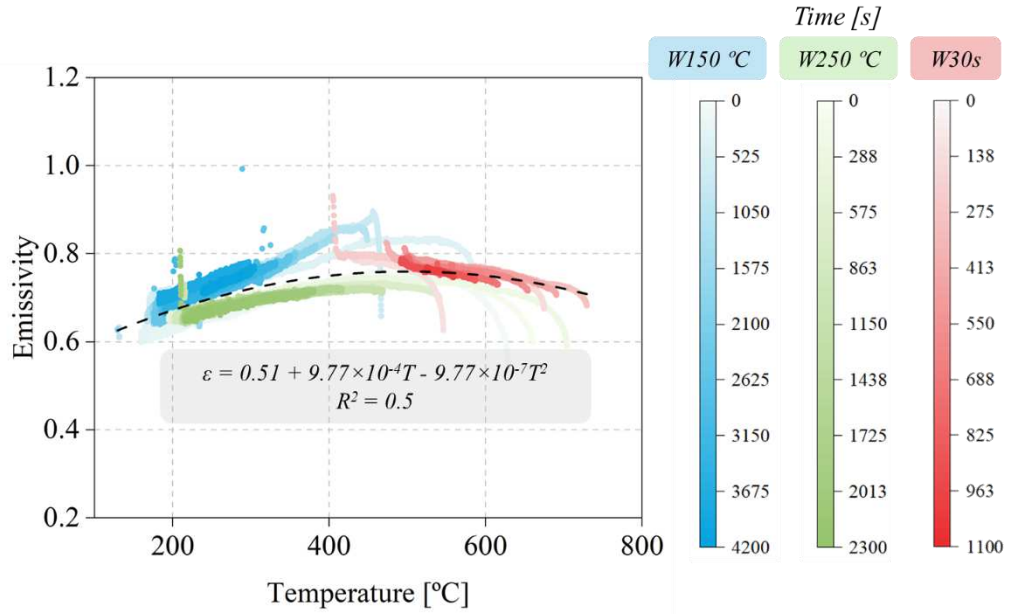


Figure 4 – Evolution of instantaneous emissivity with temperature during the cooling phase for the W150, W250, and W30s deposition strategies.

Table 4 – Average temperature error for different emissivity calibration strategies.

Wall ID	Error [%]		
	$\varepsilon = 0.71$	$\varepsilon = 0.76$	$\varepsilon = 0.51 + 9.77 \times 10^{-4} \times T - 9.77 \times 10^{-7} \times T^2$
W150	5.35	7.02	4.61
W250	3.44	6.77	3.85
W30s	5.18	1.76	2.74
Average	4.66	5.18	3.73

3.2 Thermal history and cooling rates

To comprehensively evaluate the thermal behaviour of the three deposition strategies, the maximum temperature within the infrared camera field of view was extracted continuously throughout the manufacturing process. The temperature histories were reconstructed using the calibrated emissivity approach. More specifically, Eq. (1) was applied over the temperature range from 150 to 800 °C. Outside this interval, the emissivity was kept constant at the value predicted by Eq. (1) at the nearest temperature boundary, thereby avoiding extrapolation of the fitted relationship. Accordingly, a constant emissivity of $\varepsilon = 0.63$ was adopted for temperatures below 150 °C, corresponding to the value predicted by Eq. (1) at the lower boundary. Likewise, $\varepsilon = 0.66$ was used for temperatures above 800 °C, corresponding to the value predicted at the upper boundary. Figure 5a to c present the resulting global thermal histories, with the critical

metallurgical cooling boundaries of 800 and 500 °C explicitly highlighted for determination of the $\Delta t_{8/5}$ cooling time.

The thermal histories clearly reveal distinct behaviours depending on the interpass strategy adopted. Walls W150 and W250 exhibited similar cyclic responses, characterized by repeated heating and cooling stages associated with successive layer deposition. For both walls, during cooling the temperature crossed the 500 °C threshold, thus allowing the calculation of $\Delta t_{8/5}$ for all analysed layers. In contrast, for the W30s wall, owing to the fixed interpass dwell time of 30 s the deposition sequence promoted heat accumulation, resulting in progressively higher baseline temperatures and a substantial increase in interpass temperature with layer number. Therefore, the cooling stage no longer reached 500 °C after the first layers, preventing the determination of the $\Delta t_{8/5}$ for this condition.

As shown in Figure 5d, the blue and green curves represent the evolution of the $\Delta t_{8/5}$ cooling times for W150 and W250, respectively, and should be read against the left-hand y-axis. In contrast, the red curve represents the interpass temperature of W30s and should be read against the right-hand y-axis. The arrows in the figure indicate the corresponding y-axis for each dataset. The W150 and W250 walls exhibit highly stable, periodic thermal cycles. Since the deposition of each subsequent layer is delayed until the component cools to a predefined temperature threshold, the component reaches a thermal quasi-steady state. Consequently, the $\Delta t_{8/5}$ parameter remains notably constant layer after layer. The average $\Delta t_{8/5}$ for the W150 wall was 22.1 s, whereas the W250 wall exhibited a longer cooling time of 26.6 s. This deceleration in cooling kinetics for the W250 condition is a direct physical consequence of the higher interpass temperature, which reduces the conductive thermal gradient between the localized melt pool and the underlying solid substrate.

For the W30s wall, after the first layers, the interpass temperature rose rapidly and then approached a quasi-stabilized regime at approximately 730 °C. This shows that the subsequent layers were deposited onto a wall that remained at a very high temperature, drastically reducing the effective cooling capacity of the process.

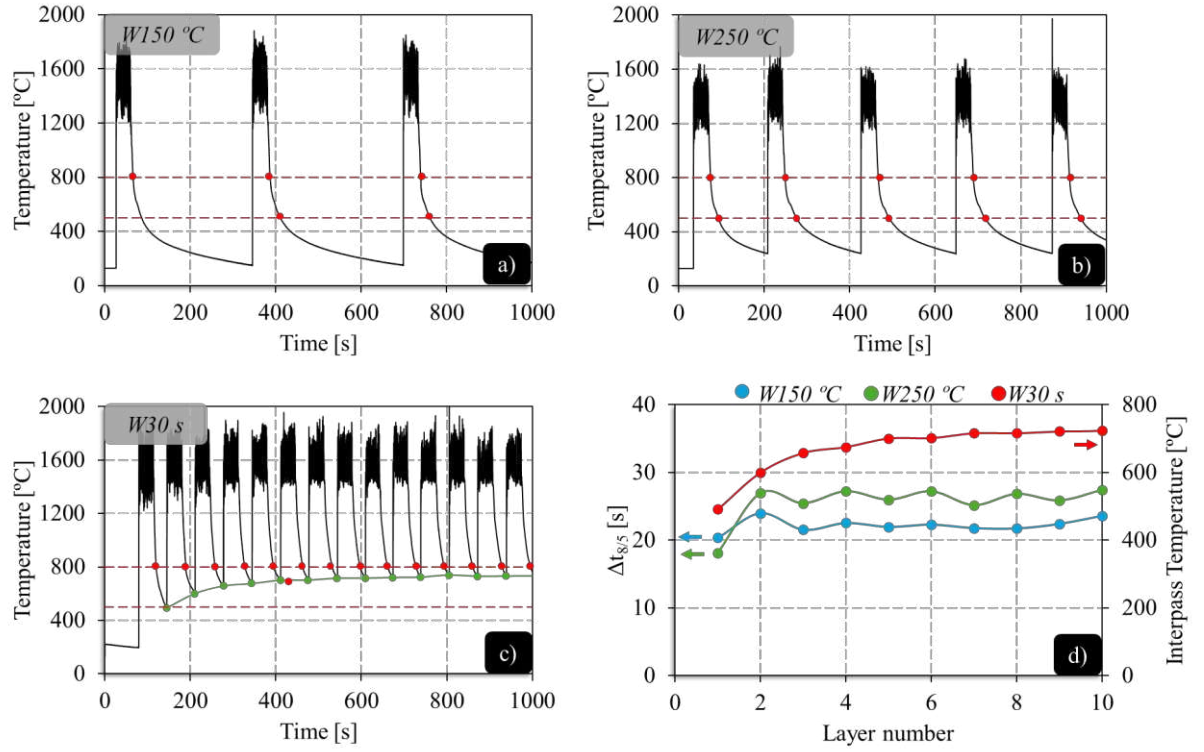


Figure 5 – Thermal evolution during DED-Arc deposition. (a–c) Maximum captured temperature profiles for the W150, W250, and W30s deposition strategies. (d) Layer-by-layer evolution of the $\Delta t_{8/5}$ cooling time for W150 and W250, plotted against the left y-axis, and of the interpass temperature for W30s, plotted against the right y-axis. Arrows indicate the corresponding y-axis for each dataset.

Figure 6 highlights the sensitivity of the thermography-based thermal metrics to the emissivity value adopted in the data reduction procedure. Specifically, Figure 6a shows the evolution of the nominal $\Delta t_{8/5}$ values for walls W150 and W250, plotted against the left y-axis, together with the nominal interpass temperature for wall W30s, plotted against the right y-axis, when different constant emissivity values are assumed instead of the emissivity correction defined by Eq. (1). In all cases, a strong non-linear dependence on emissivity is observed. As emissivity increases, the estimated thermal outputs decrease markedly, following a power-law trend. This behaviour is particularly relevant at low emissivity values, where small changes in ε lead to large variations in the calculated thermal parameters, whereas at higher emissivity the curves progressively flatten, indicating a lower sensitivity of the outputs to emissivity changes.

This non-linear amplification is further corroborated by Figure 6b, which presents the absolute error of the calculated outputs relative to the reference values obtained using the emissivity correction of Eq. (1). For emissivity values approaching $\varepsilon = 0.7$, the deviations remain marginal, generally below 10%, suggesting that this range offers a reasonable approximation for practical monitoring purposes. However, the adoption of

lower constant emissivity yields rapidly escalating errors. For example, at $\varepsilon = 0.4$, the error reaches approximately 131% for the $\Delta t_{8/5}$ of the W150 wall, 79% for W250, and 47% for the interpass temperature of W30s. Consequently, utilising an inadequate, constant emissivity may lead to a severe overestimation of both the cooling time and the interpass temperature. This artificially distorts the interpretation of the thermal history, ultimately compromising the ability to reliably predict the microstructural evolution and the resulting mechanical properties of the deposited material.

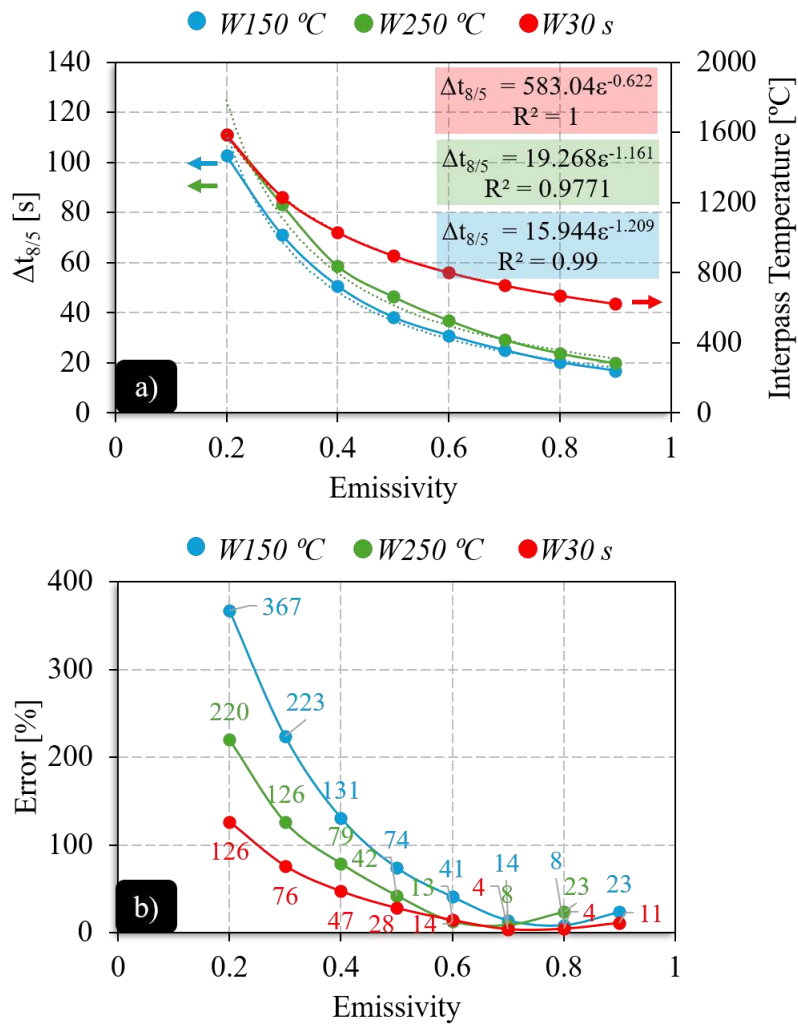


Figure 6 – Sensitivity of the extracted thermal metrics to the emissivity assumed in the thermographic analysis: (a) variation of the nominal $\Delta t_{8/5}$ values for walls W150 and W250 (left y-axis), and of the nominal interpass temperature for wall W30s (right y-axis), as a function of constant emissivity; (b) corresponding absolute error of these thermal metrics relative to the reference values obtained using the temperature-dependent emissivity correction defined by Eq. (1).

3.3 Microstructural evolution and microhardness

The influence of the interpass control strategy on the resulting microstructure was assessed through optical microscopy and quantitative grain-size analysis. Figure 7 compares representative etched micrographs, grain size maps and the corresponding equivalent grain-size distributions for the W150, W250 and W30s walls. The segmented maps are coloured according to the equivalent grain diameter, allowing the spatial variation in grain size to be directly visualised.

The W150 and W250 conditions exhibited comparable ferritic microstructures, characterised by relatively fine polygonal grains and a heterogeneous distribution of smaller and larger grains. The mean equivalent grain diameters were $7.8 \pm 5.4 \mu\text{m}$ for W150 and $8.4 \pm 5.1 \mu\text{m}$ for W250. The limited difference between these values indicates that increasing the controlled interpass temperature from 150 to 250 °C produced only a modest change in the average grain size under the processing conditions investigated.

A markedly different grain morphology was observed in the W30s condition. Although this wall also exhibited a ferritic microstructure, it was characterised by substantially larger grains, with several coarse-grained regions clearly visible in both the optical micrograph and the grain map. The mean equivalent grain diameter increased to $12.6 \pm 8.9 \mu\text{m}$, corresponding to an increase of approximately 62% relative to W150 and 50% relative to W250. The larger standard deviation also indicates a broader grain-size distribution and greater microstructural heterogeneity. This is consistent with the coexistence of relatively fine grains and isolated coarse-grained regions observed in Figure 7f.

These differences can be directly related to the thermal histories described in Section 3.2. The temperature-controlled W150 and W250 conditions exhibited similar quasi-steady thermal cycles, which resulted in comparable ferritic microstructures, with only a modest difference in mean equivalent grain size. In contrast, the prolonged thermal exposure experienced by W30s reduced the effective cooling capacity of the wall and promoted repeated reheating at elevated temperatures. These conditions favoured grain-boundary migration and grain coarsening, resulting in a substantially larger and more heterogeneous grain structure.

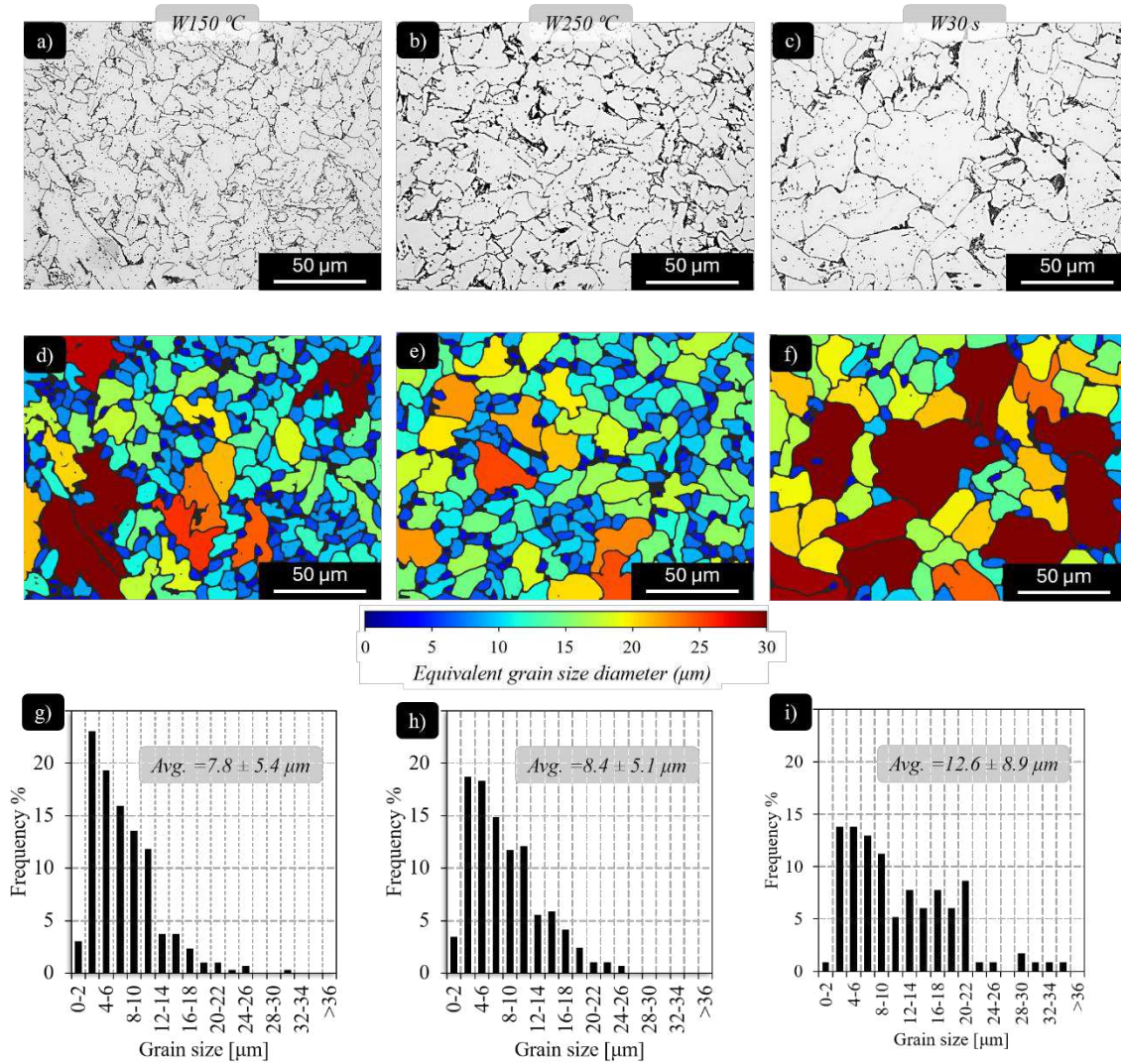


Figure 7 – Microstructural characterisation of the DED-Arc walls produced under different interpass strategies: (a–c) representative etched optical micrographs of W150, W250 and W30s; (d–f) corresponding segmented grain maps coloured according to the equivalent grain diameter; and (g–i) equivalent grain-size distributions. The reported values represent the mean equivalent grain diameter $\pm$ standard deviation.

Figure 8 presents the Vickers microhardness profiles measured along the build direction of the W150, W250 and W30s walls. The three conditions exhibited relatively uniform hardness distributions over the analysed wall height, although local fluctuations were observed. The W150 wall exhibited the highest average microhardness, with a value of 159 ± 4 HV_{0.5}, while W250 showed a slightly lower but comparable average value of 156 ± 4 HV_{0.5}. The close agreement between these two conditions is consistent with their similar thermal histories and grain size distribution. In contrast, the W30s wall exhibited the lowest average microhardness, 148 ± 5 HV_{0.5}. This corresponds to reductions of

approximately 7% and 5% relative to W150 and W250, respectively. The lower hardness is consistent with the coarser grain structure observed in Figure 7.

The hardness profiles also show that W30s generally remained below the temperature-controlled conditions throughout the analysed build height. Nevertheless, no pronounced monotonic hardness gradient was observed for any of the walls. Instead, the local oscillations suggest that hardness was influenced by the sequence of overlapping thermal cycles and by the location of the measurements relative to the individual deposited layers and reheated interpass regions.

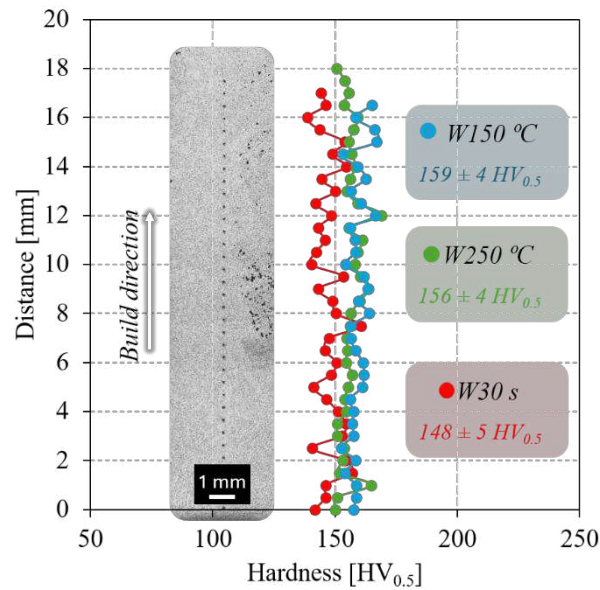


Figure 8 – Vickers microhardness profiles measured along the build direction of the W150, W250 and W30s walls.

3.4 Mechanical properties and process-property correlation

Building on the thermal analysis, this section examines how the differences in thermal history are reflected in the mechanical response of the deposited walls. Figure 9 shows the representative engineering tensile stress-strain curves for all tested walls, together with the von Mises strain maps obtained by DIC at maximum load. The results show that all walls exhibited the typical response of low-carbon steel, with an initial linear elastic regime followed by yielding, progressive plastic deformation, and final failure. A more detailed comparison indicates that walls W150 and W250 displayed very similar tensile responses, whereas wall W30s exhibited clearly inferior strength. The DIC strain maps further show that deformation remained relatively homogeneous along the gauge length up to maximum load, with no evident strain localisation associated with major

internal discontinuities or defects that could have promoted premature failure. This observation suggests that the tensile response was primarily governed by intrinsic material behaviour rather than by macroscopic manufacturing defects.

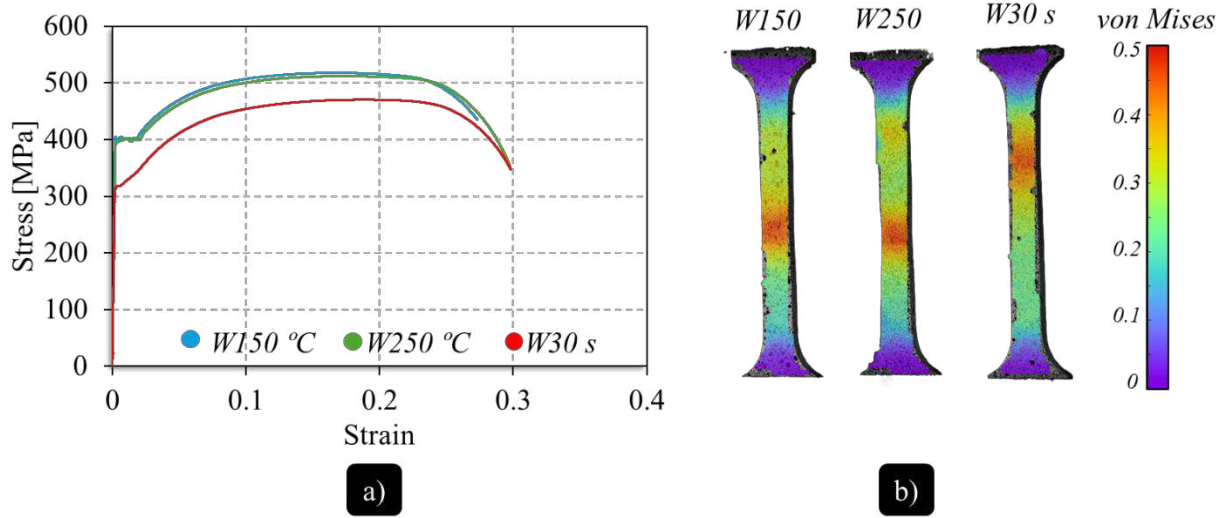


Figure 9 –Representative (a) engineering tensile stress–strain curves and (b) von Mises strain maps at maximum load for the tested walls.

Figure 10a summarises the main tensile properties, namely the yield strength (f_y), ultimate tensile strength (f_u), and ultimate strain (ϵ_u). The corresponding average values and standard deviations are detailed in Table 5. For comparison with conventional structural steels, the minimum requirements specified in EN 10025-3 [32] for S355 steel are superimposed in Figure 10a as red reference lines. The results show that wall W150 exhibited the highest yield strength, followed closely by W250, while both conditions reached essentially the same ultimate tensile strength of 515 MPa. In contrast, W30s showed the lowest strength levels, with an average yield strength of 334 MPa and an average ultimate tensile strength of 470 MPa. However, this wall also exhibited the highest ductility, with an ultimate strain of approximately 31%, slightly above that of W150 and comparable to W250.

These trends are consistent with the differences in thermal history previously identified. As discussed in Section 3.2, the W30s wall experienced the highest interpass temperatures, reaching average values substantially above those measured under controlled interpass conditions. Such thermal accumulation slower cooling and longer times at elevated temperature, have been related to the formation of a coarser microstructure dominated by ferritic and pearlitic constituents [27,28], which explains the lower strength and slightly higher ductility observed for W30s. By contrast, the controlled

thermal conditions imposed in W150 and W250 led to lower interpass temperatures and faster cooling, thereby promoting a finer microstructure and, consequently, higher mechanical properties.

The W30s condition also exhibited larger dispersion, particularly in yield strength, than W150 and W250. As shown in Section 3.2, the W30s wall experienced a progressive increase in interpass temperature with build height, which implies that different layers were deposited under different thermal conditions. This thermal heterogeneity is expected to generate greater microstructural variation throughout the wall height and, consequently, less uniform mechanical properties.

When compared with the minimum values required for S355 structural steel according to EN 10025-3 [32], the W150 and W250 walls clearly satisfied the specified thresholds for both yield and ultimate tensile strength. In the case of W30s, the larger scatter implied that some individual results may fall close to or below the specified yield strength threshold. Nevertheless, all fabricated walls fulfilled the ductility-related requirements commonly adopted for safe structural application according to EN 1993-1-1 [33], including elongation at fracture $\varepsilon_f > 15\%$, ultimate strain $\varepsilon_u > 15 \varepsilon_y$ (where $\varepsilon_y = f_y/E$ is the yield strain and E is Young's modulus) and a tensile-to-yield strength ratio $f_u/f_y \geq 1.10$. As shown in Table 5, these criteria were consistently satisfied for all deposition conditions.

Figure 10b further examines the process-property relationship by plotting f_y, f_u and ε_u as a function of interpass temperature. For the W30s wall, an average interpass temperature of 730 °C was considered, as established in Section 3.2. The results indicate that both f_y and f_u decrease with increasing interpass temperature, whereas ε_u shows a slight increasing tendency.

Although emissivity does not affect the tensile properties experimentally measured for the produced walls, it may influence the way these properties are correlated with the thermal history extracted from infrared thermography. Combining the fitted relations of Figure 6 and Figure 10b, for the W30s wall, the interpass temperature varied with emissivity according to $T = 583.04 \varepsilon^{-0.622}$, while the tensile properties were correlated with interpass temperature through power-law relations. By combining these expressions, the apparent emissivity dependence of the tensile properties was determined as $f_y \propto \varepsilon^{0.037}$, $f_u \propto \varepsilon^{0.075}$ and $\varepsilon_u \propto \varepsilon^{-0.031}$. For instance, assuming an uncalibrated emissivity of 0.4 instead of a calibrated value of 0.7 artificially inflates the assigned interpass temperature by nearly 300 °C, which consequently affects the predicted yield strength by approximately

14 MPa, which can cause the false classification of a component's structural compliance (e.g., failing the S355 standard). This indicates that emissivity uncertainty does not directly alter the measured tensile properties, but instead affects the thermal variables used to interpret them. Consequently, the main impact of inadequate emissivity calibration is the distortion of the thermal history assigned to each deposition condition, which may bias the inferred process-property correlation. Although only indicative, this analysis further highlights the importance of emissivity calibration when thermography is used to establish quantitative links between thermal history and mechanical performance.

Table 5 – Summary of the uniaxial tensile properties for the DED-Arc walls.

Sample	f_y [MPa]	f_u [MPa]	ϵ_u [%]	f_u/f_y	$15\epsilon_y$ [%]
<i>W150</i>	401 ± 2	515 ± 3	28 ± 1	1.28	3.02
<i>W250</i>	395 ± 4	515 ± 3	31 ± 2	1.31	3.44
<i>W30s</i>	334 ± 19	470 ± 12	31 ± 1	1.40	3.37

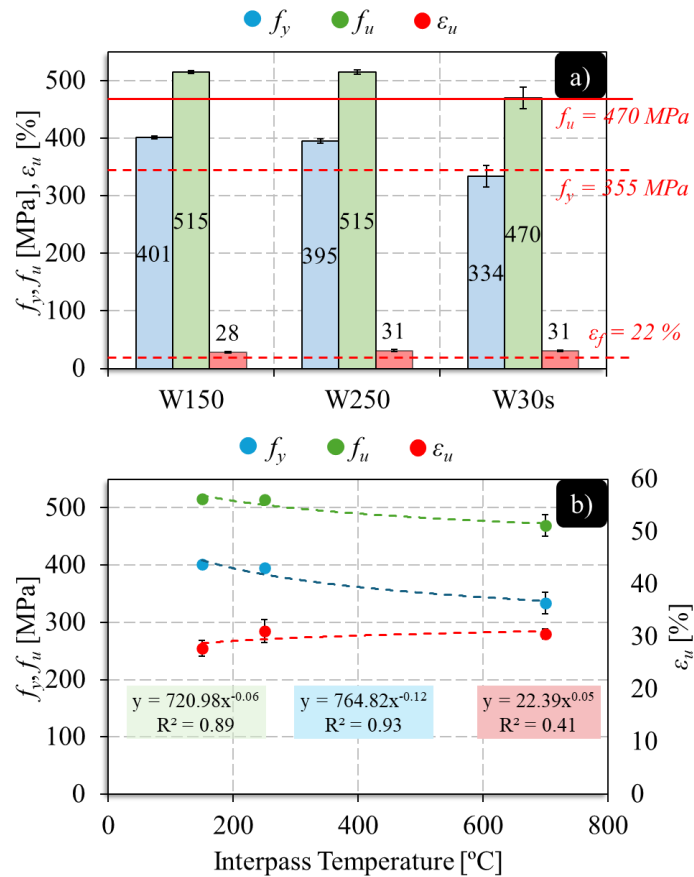


Figure 10 – Mechanical properties of the deposited walls: (a) average yield strength (f_y), ultimate tensile strength (f_u), and ultimate strain (ϵ_u) compared to the minimum requirements for S355 structural steel; (b) correlation between the mechanical properties and the measured interpass temperature.

4 Conclusions

The present work evaluated the effectiveness of infrared thermography for thermal monitoring in carbon steel DED-Arc, with a primary focus on in-situ emissivity calibration. Based on the experimental findings, the main conclusions are as follows:

- The results showed that the use of a single arbitrary emissivity may lead to significant deviations in the measured temperatures, particularly under conditions of strong heat accumulation. The optimum constant emissivity was 0.71 for the 150 °C and 250 °C walls and 0.76 for the 30 s wall, while a temperature-dependent emissivity law provided the best overall agreement with the thermocouple measurements, reducing the average error in temperature acquisition to 3.73%.
- The walls produced under temperature-based interpass control exhibited comparatively stable thermal cycles, with average $\Delta t_{8/5}$ values of 22.1 s for W150 and 26.6 s for W250. In contrast, the fixed 30 s interpass strategy led to pronounced heat accumulation, with interpass temperatures approaching 730 °C, which prevented reliable $\Delta t_{8/5}$ determination after the first deposited layers.
- The tensile results showed that the two temperature-controlled conditions provided the best mechanical performance. W150 and W250 exhibited similar ultimate tensile strengths of 515 MPa, with yield strengths of 401 MPa and 395 MPa, respectively, indicating that both conditions were able to maintain satisfactory strength levels. By contrast, the W30s wall showed a marked reduction in strength, with 470 MPa ultimate tensile strength and 334 MPa yield strength, although with slightly higher ductility.
- From an engineering standpoint, the results demonstrate that infrared thermography can be used as an effective tool for in-situ monitoring of DED-Arc steel components, if emissivity is properly calibrated. Moreover, temperature-based interpass control was shown to be more robust than fixed-time deposition, since it ensures more stable thermal conditions and better mechanical performance. The work therefore contributes to a more reliable use of thermography in arc-based additive manufacturing and supports the implementation of more consistent thermal control strategies for structural steel applications.

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Data availability All the data presented and/or analyzed in this study are available upon request to the corresponding author.

Declarations

Conflict of interest: Not applicable.

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