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Wire arc directed energy deposition of 18Ni-350 maraging steel: process optimization, mechanical properties and aging response

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Abstract

Wire arc directed energy deposition (WA-DED) offers an economically viable route for the additive manufacture of large-scale maraging steel components, yet systematic process–property relationships for the 18Ni-350 grade remain scarce. This work establishes an optimized processing window for 18Ni-350 maraging steel deposited under short-circuit transfer and characterizes the mechanical and microstructural response in both as-built and aged (480 °C/5 h) conditions. A circumscribed central composite design modeled arc stability, quantified through a voltage-amplitude index, as a function of travel speed, wire feed speed and voltage. Voltage, wire feed speed and their interaction were the dominant factors, yielding an optimum at TS = 481 mm/min, WFS = 5.9 m/min and V = 23.4 V with a predicted stability of 96.3%. Single-bead walls produced under these parameters reached ultimate tensile strengths of 1253–1366 MPa as-built, rising to 1613–1687 MPa after aging, while elongation increased from 5.9–6.6% to 8.5–10.2%, consistent with an incipient over-aged state and partial homogenization of as-deposited heterogeneities. Multi-bead thick walls deposited with a four-bead-per-layer strategy reached 508±10 HV1.0 as-built and 625±9 HV1.0 after aging, while Charpy V-notch impact energy remained unchanged (438±2 J vs. 440±3 J). The contrast between pronounced hardness response and negligible toughness variation is consistent with fracture-controlling microstructural features being established during the multi-bead

thermal history, supporting WA-DED as a viable route to high-strength, impact-tolerant near-net-shape 18Ni-350 components.

Keywords: Additive Manufacturing; Wire arc directed energy deposition; Maraging steel; 18Ni-350; Design of experiments; Arc stability; Aging heat treatment

1. Introduction

Additive manufacturing (AM) technologies rely on the deposition of successive layers of material until the desired geometry is achieved. Compared to traditional manufacturing technologies, AM offers advantages such as reduced material waste, shorter lead times, design flexibility, and, in some cases, the possibility of eliminating post-production assembly operations [1].

Among metal AM processes, wire arc directed energy deposition (WA-DED), also known as wire arc additive manufacturing (WAAM), has garnered considerable industrial interest due to the capability to produce large-scale, near-net shape components with complex geometries at high deposition rates, while using comparatively low-cost equipment [2]. These advantages have resulted in growing adoption of this manufacturing technology in sectors where complex geometries and part iteration are critical, such as the aerospace, automotive, tooling, or energy [3].

WA-DED's working principles are based on arc welding processes where an electric arc is used as a heat source, melting the feedstock wire and consequently depositing the molten material onto a substrate. This process can be leveraged on the several existing arc welding technologies such as gas metal arc welding (GMAW), gas tungsten arc welding (GTAW), plasma arc welding (PAW), or cold metal transfer (CMT) with each of these offering specific trade-offs between deposition rates, control of heat input and

process stability [4]. When compared to powder-based metal AM processes, such as laser powder bed fusion (LPBF), WA-DED requires lower capital investment, achieves higher material usage, usually over 90%, and achieves deposition rates up to 10 kg.h⁻¹ [5].

Maraging steels represent a class of high-strength, low carbon steels whose strength derives from a soft martensitic matrix and age hardening by the precipitation of densely distributed intermetallic precipitates, such as Ni₃ (Ti, Al, Mo) and Fe₂Mo, which form during aging at a temperature of 450 to 510°C [6]. Ultimate tensile strength (UTS) reported in literature varies between 1.0 to 3.4 GPa, depending on the grade of the alloy and the heat treatment applied [7]. Their low carbon content, generally below 0.03wt.%, allows for excellent weldability and dimensional stability during aging while the high Ni, Co, Mo, and Ti contents enable a balance between strength, toughness, and fracture resistance [8, 9]. These characteristics have made maraging steels desirable for industries where high strength to weight ratio and tight dimensional tolerances are required with reported usages in the manufacture of rocket motor cases [10], aircraft structural components, fasteners or high-performance tooling and dies [11].

The application of maraging steels to the production of components using AM processes has been extensively studied for powder-based processes, mainly LPBF, demonstrating that additively manufactured maraging steels can achieve microstructural and mechanical properties comparable to conventionally produced counterparts when appropriate process parameters and heat treatments are used [12]. However, AM related flaw formation, accumulation of heat, and process induced microstructural heterogeneities can affect the mechanical performance of the component. For example, Bouzakis et al [13] has reported that LPBF maraging steel samples provided lower fatigue and corrosion-fatigue properties when compared to bulk while Pustički et al. [14] reported increased susceptibility to corrosion caused by sub-surface porosity and oxides.

1 Compared to powder-based AM options, WA-DED processing of maraging steels has
2 received limited attention, despite its economic and scalability advantages, as well as
3 repair-oriented characteristics. Early studies using CMT established the feasibility of
4 using WA-DED to deposit defect free bulk maraging steel components and assessed that
5 depositing in a weaving pattern was an effective strategy [7]. Post processing studies
6 demonstrate that conventional heat treatment remains highly effective in the WA-DED
7 processed maraging steel. Kan *et al.* [15] showed that a solution treatment at 840°C
8 followed by aging at 480°C for 4 hours resulted in a uniform dispersion of Ni₃Ti and
9 Ni₃Mo nanoprecipitates, increasing the UTS to approximately 1.7 GPa, presenting close
10 values to those obtained via conventionally processed maraging steels under the same
11 heat treatment.

12 Recently, studies have shifted the focus towards exploiting the intrinsic thermal cycles
13 characteristic of WA-DED as in-situ heat treatment and to the control of heat input. Xu *et*
14 *al.* [16] used WA-DED to deposit 250 maraging steel thin wall structures using CMT to
15 investigate the effect of thermal cycles as an in-situ heat treatment in the microstructural
16 properties of the as-deposited part. Zhang et al [17] investigated the effect of heat input
17 in the properties of 18Ni 300 maraging steel produced using WA-DED with different
18 modes (Pulsed GMAW, CMT and a hybrid CMT + Pulsed GMAW). Lower heat input
19 was found to reduce the ferrite fraction, impact texture, and improve the tensile properties,
20 highlighting the importance of optimization of process parameters for property control.

21 Despite these advancements in research, the identification of optimal processing
22 windows for WA-DED of maraging steels and the relationship of these with resulting
23 microstructural and mechanical properties remains a significant gap in existing literature.
24 This is particularly relevant for the 18Ni-350 maraging steel, for which systematic studies
25 on WA-DED processing, parameter optimization, and resulting property profiles are

scarce. As such, the present research aims to optimize the process parameters of WA-DED for 18Ni-350 maraging steel (using the commercial UTP A 702 feedstock wire) using a statistical Design of Experiments (DoE) methodology, defining a stable process window suitable for near-net-shape production. Furthermore, the microstructural and mechanical properties of the fabricated components are examined and discussed providing insight into the process-part-property relationships.

This paper is organized as follows: Section 2 describes the WA-DED system and the feedstock material used, the design of experiments and the arc-stability metric, together with the sample production and the mechanical and microstructural characterization procedures. Section 3 presents the discussion regarding the response surface optimization of process parameters, followed by tensile behavior, microhardness, impact toughness, and microstructural evolution of the deposited material in both the as-built and aged conditions. Section 4 summarizes the main conclusions and outlines the future work.

2. Materials and Methodology

WA-DED samples were produced using a Promig NG 450W torch integrated into an in-house developed three-axis gantry. Thin wall depositions were performed using a 350 maraging steel wire with a diameter of 1.2 mm, commercialized by Voestalpine under the trade name UPT A 702, with the composition detailed in Table 1. The welding torch was connected to a Lincoln Electric CITOWAVE III 520 power source and a DMU W500 wire feeder. The experiments were conducted in manual mode, both Wire Feed Speed (WFS) and Voltage were manually defined, while the current fluctuated according to the transfer characteristics. For shielding gas, pure Ar with a flow rate of 18 L/min was used.

Table 1 – UTP A 702(1.6356) maraging steel chemical composition (wt. %).

C	Mo	Ni	Co	Ti	Al	Fe
0.02	4.0	18.0	12.0	1.6	0.1	Balance

In the conditions applied throughout this work, the transfer mode was predominantly characterized by short-circuit, with the waveform analysis confirming the predominance of this mode. This mechanism can be described in two main phases: the arcing period, during which a droplet forms at the wire tip, and the short-circuit period, when the droplet is transferred to the base metal upon contact. These cycles give rise to synchronized fluctuations in voltage and current. It should be noted, however, that depending on the specific combinations of process parameters (e.g., current, voltage, and wire feed speed), other transfer modes may also have taken place [18]. Nevertheless, short-circuit transfer was the most frequently observed and therefore served as the basis for the considerations developed in this work.

2.1. Design of experiments and process parameter optimization

With the purpose of optimizing the parameters of the WA-DED process for the feedstock material considered, a Design of Experiments (DoE) approach based on Response Surface Methodology (RSM) was implemented. Considering DED-arc is a multivariate process, this approach allows for a structured assessment of optimal process parameters space while minimizing the quantity of trial-and-error experiments [19]. In this research, the relationship between process parameters and the characteristics of single-bead depositions were modeled to assess the enhanced processing parameters.

A Central Composite Design (CCD) was used to build a quadratic response surface model. The experimental plan considered a 2^k factorial core, axial points and center points, where k indicates the number of process variables considered. This configuration provides sufficient curvature for modeling second-order effects and ensures rotatability of the design. A Circumscribed Central Composite Design (CCC) was selected to cover a wider domain of the parameter space. For this, each factor was studied at 5 levels, $-\alpha$, -1 , 0 , $+1$, $+\alpha$, where $\pm\alpha$, defined by Eq. 1 that represents the distance between the star points

and the center, making the planning rotatable. The total number of experiments required to fulfil this DoE results from the sum of the factorial, axial and center runs.

$$\alpha = (2^k)^{\frac{1}{4}} \quad (1)$$

The experimental responses were expressed as functions of the process variables using a second order polynomial model, which includes linear, quadratic and interaction terms. The regression coefficients were estimated using the least squares method while the statistical significance of each of the terms and the overall model were evaluated through analysis of variance (ANOVA).

From ANOVA, sums of squares, mean squares, F-values and associated p-values were obtained to assess which factors and interactions have a significant influence on the responses. Complementary metrics such as R^2 , adjusted R^2 and predicted R^2 were used to evaluate the goodness of fit and predictive capability of the model.

Additionally, to check for model adequacy and to identify the most influential terms, other diagnostics tools such as residual plots and Pareto charts were analyzed. Residual analyses were used to verify normality, homoscedasticity and independence assumptions, while Pareto charts highlighted the significant main and interaction effects. After model validation, confirmation runs were performed to verify the predictive performance of the optimized parameter set.

Based on preliminary experimental process parameter assessment and literature survey on the MIG-based DED-arc production of 350 maraging steels, suitable ranges of wire feed speed (WFS), torch travel speed (TS), and voltage were defined as presented in Table 2 [20, 21]. These ranges were selected to ensure consistent and stable material transfer, avoid excessive heat input and obvious geometrical flaws on the produced layers.

Table 2 - Range of parameters used on the design of experiments.

WFS	TS	Voltage
2.5 – 5.0 m/min	240 – 420 mm/min	18 – 22 V

As such, these three factors were considered in the DoE due to their ability to control the balance between deposition rate, heat input and process stability. Among the numerous output variables that can be extracted from the process and resulting layers, the stability of the electric arc was chosen as the primary response due to its critical role in ensuring consistent heat and material transfer and layer quality [22]

Considering the range of parameters and the previously described DoE, three repetitions per combination of parameters were used, with 20 unique experiments per replicate, totaling 60 experimental runs, detailed in Table 3. To ensure statistical validity and to prevent systematic errors and time-based biases, the 60 experimental runs were randomized in the Minitab software.

1 Table 3 – Experimental parameters used on each of the runs that composes the optimization of parameters.

Run	TS	WFS	V	Run	TS	WFS	V
1	240 [-1]	5 [1]	18 [-1]	31	240 [-1]	5 [1]	18 [-1]
2	330 [0]	3,8 [0.04]	20 [0]	32	420 [1]	2,5 [-1]	18 [-1]
3	420 [1]	2,5 [-1]	18 [-1]	33	330 [0]	1,6 [-1.72]	20 [0]
4	240 [-1]	2,5 [-1]	18 [-1]	34	420 [1]	5 [1]	22 [1]
5	330 [0]	5,9 [1.72]	20 [0]	35	330 [0]	5,9 [1.72]	20 [0]
6	420 [1]	5 [1]	22 [1]	36	330 [0]	3,8 [0.04]	23,4 [1.7]
7	330 [0]	3,8 [0.04]	20 [0]	37	420 [1]	2,5 [-1]	22 [1]
8	178,6 [-1.68222]	3,8 [0.04]	20 [0]	38	330 [0]	3,8 [0.04]	16,6 [-1.7]
9	481,4 [1.68222]	3,8 [0.04]	20 [0]	39	240 [-1]	2,5 [-1]	18 [-1]
10	330 [0]	3,8 [0.04]	16,6 [-1.7]	40	330 [0]	3,8 [0.04]	20 [0]
11	420 [1]	5 [1]	18 [-1]	41	330 [0]	5,9 [1.72]	20 [0]
12	330 [0]	3,8 [0.04]	23,4 [1.7]	42	420 [1]	5 [1]	18 [-1]
13	330 [0]	3,8 [0.04]	20 [0]	43	330 [0]	3,8 [0.04]	20 [0]
14	330 [0]	3,8 [0.04]	20 [0]	44	420 [1]	2,5 [-1]	18 [-1]
15	420 [1]	2,5 [-1]	22 [1]	45	420 [1]	2,5 [-1]	22 [1]
16	240 [-1]	2,5 [-1]	22 [1]	46	178,6 [-1.68222]	3,8 [0.04]	20 [0]
17	240 [-1]	5 [1]	22 [1]	47	240 [-1]	5 [1]	18 [-1]
18	330 [0]	3,8 [0.04]	20 [0]	48	330 [0]	3,8 [0.04]	23,4 [1.7]
19	330 [0]	1,6 [-1.72]	20 [0]	49	330 [0]	1,6 [-1.72]	20 [0]
20	330 [0]	3,8 [0.04]	20 [0]	50	330 [0]	3,8 [0.04]	20 [0]
21	420 [1]	5 [1]	18 [-1]	51	330 [0]	3,8 [0.04]	20 [0]
22	240 [-1]	5 [1]	22 [1]	52	330 [0]	3,8 [0.04]	16,6 [-1.7]
23	330 [0]	3,8 [0.04]	20 [0]	53	420 [1]	5 [1]	22 [1]
24	178,6 [-1.68222]	3,8 [0.04]	20 [0]	54	330 [0]	3,8 [0.04]	20 [0]
25	481,4 [1.68222]	3,8 [0.04]	20 [0]	55	240 [-1]	5 [1]	22 [1]
26	330 [0]	3,8 [0.04]	20 [0]	56	240 [-1]	2,5 [-1]	22 [1]
27	330 [0]	3,8 [0.04]	20 [0]	57	330 [0]	3,8 [0.04]	20 [0]
28	240 [-1]	2,5 [-1]	22 [1]	58	481,4 [1.68222]	3,8 [0.04]	20 [0]
29	330 [0]	3,8 [0.04]	20 [0]	59	240 [-1]	2,5 [-1]	18 [-1]
30	330 [0]	3,8 [0.04]	20 [0]	60	330 [0]	3,8 [0.04]	20 [0]

2.2. Arc Stability Measurement

Arc stability was quantified using the voltage-amplitude Arc Stability Index (S) grounded in signal analysis theory, introduced by Suban and Tušek [22]. The Arc Stability Index was calculated using Equation 2, where μ^V is the mean and σ^V the standard deviation of the voltage signal.

$$S = 100 \times \left(1 - \frac{\sigma^V}{\mu^V}\right) [\%] \quad (2)$$

A higher value of S indicates a stable arc as there is less variation of the signal in relation to its mean value, a direct consequence of a more consistent arc length, droplet detachment and heat transfer to the meltpool [18, 22]. For this analysis, voltage data from the WA-DED process was acquired using a Digilent Analog Discovery 2 USB oscilloscope at a rate of 10 kHz. To avoid interference introduced by the power line, a 50 Hz high pass filter was applied before analysis.

It should be noted that period-based methods, that consider the time interval between consecutive short circuit events [22, 23], were considered but found unsuitable for the assessment of stability for the UTP A 702 feedstock wire. The waveform obtained for this high-alloy material displays irregular short-circuit patterns, which are ultimately inconsistent with the assumptions underlying in these methods.

2.3. Sample production

Following DoE optimization, a total of three WA-DED walls were produced using enhanced parameters, composed of two thin walls and a multi-bead thick wall with final dimensions of each wall depending on the corresponding mechanical or microstructural analysis to be conducted.

The thin walls, named Wall 1 and Wall 2, were deposited on $200 \times 60 \times 8 \text{ mm}^3$ mild steel substrate as single bead passes in a zigzag strategy. After deposition both samples were machined to a uniform thickness of 2 mm and separated from the substrate. Fig. 1 (a-b) displays Wall 1 in the as deposited conditions while Fig. 1 (c-d) shows Wall 1 and Wall 2 after the machining process and prior to the separation from the substrate.

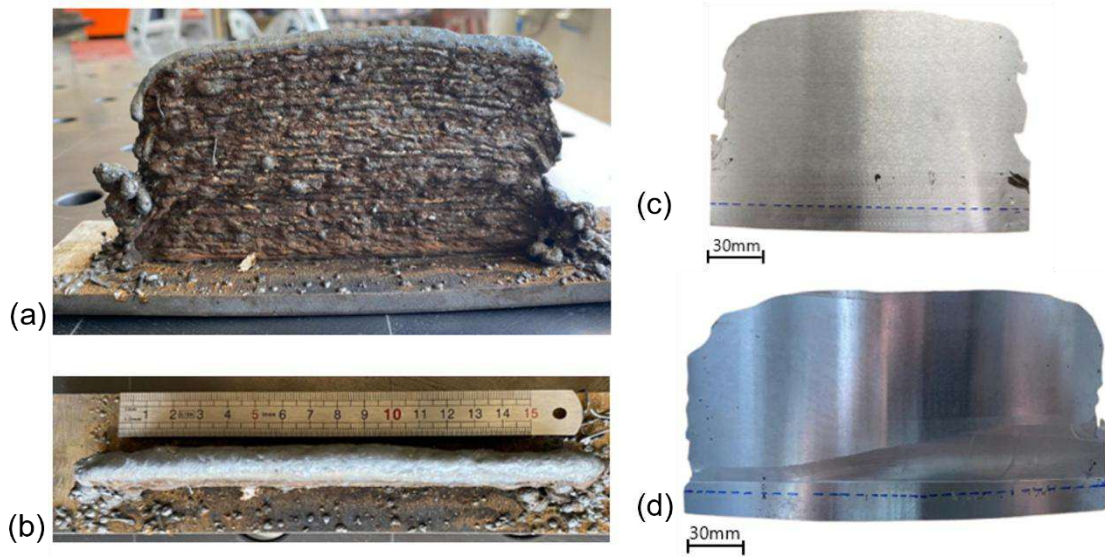


Fig. 1 – 18Ni-350 maraging steel WA-DED samples. (a) Front view of Wall 1 in the as deposited state (b) Top view. (c) Wall 1 machined. (d) Wall 2 machined. The blue line in the machined samples indicates the substrate-deposited material boundary.

The multi-bead thick wall was produced using the same optimized parameters with a four-bead-per-layer strategy (30 % bead overlap) and a zig-zag deposition scheme, as illustrated in Fig. 2. The bead thickness under these conditions was approximately 8 mm, which equated to a distance of 5.6 mm between beads.

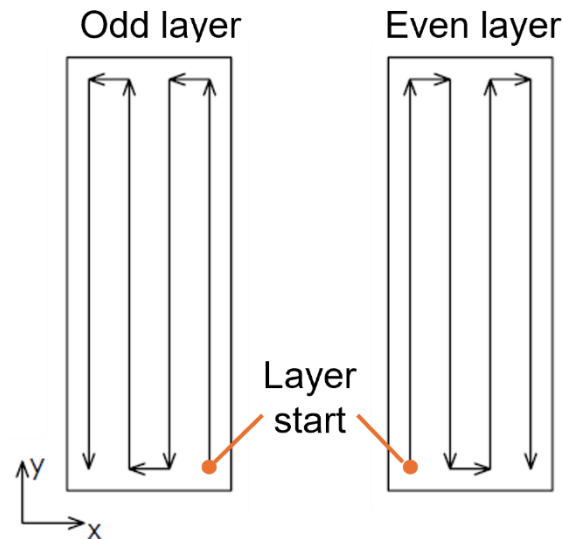


Fig. 2 - Deposition strategy used for the production of the multi-bead wall.

Tensile specimens were machined from the single bead walls using a HAAS Super Mini Mill 2, extracting in total 9 vertical and 10 horizontal specimens, as shown in Fig. 3 (a-b). The dimensions of the extracted specimens are detailed in Fig. 3 (c), with gauge dimensions of 2.0 mm and 2.5 mm width, were selected to suit the available test equipment.

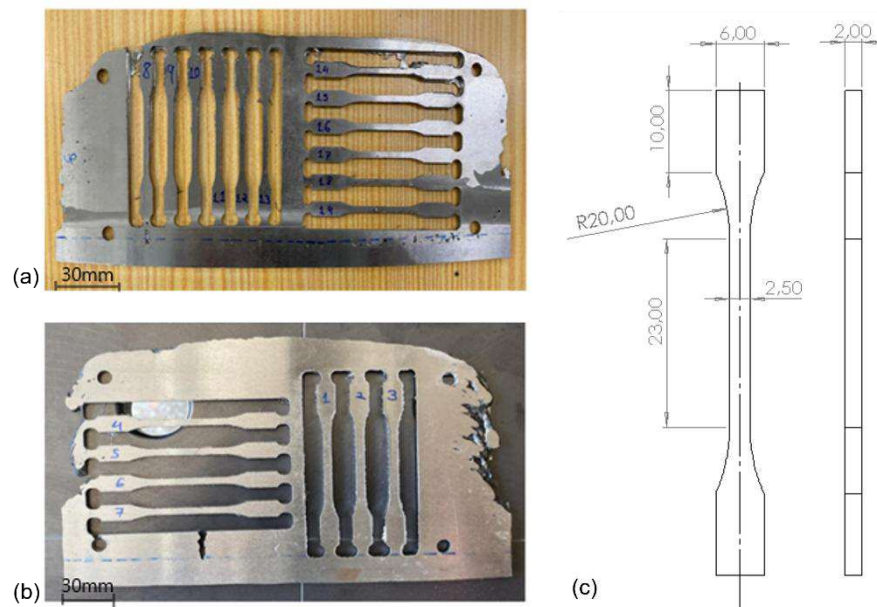


Fig. 3 - Uniaxial tensile test specimens for: (a) Wall 1, (b) Wall 2, (c) Dimensions of the specimens.

A similar procedure was applied to the multi-bead wall where specimens for Charpy V-notch impact tests, microhardness and microstructural analysis were extracted, in the

locations schematized in Fig. 4. The specimens extracted from the multi-bead wall were annotated regarding position, the specimens notated with the letter “H” were subjected to heat treatment while the rest were analyzed in the as-deposited condition. A standard aging treatment (480°C for 5 hours, followed by air cooling) was applied to the selected specimens [24].

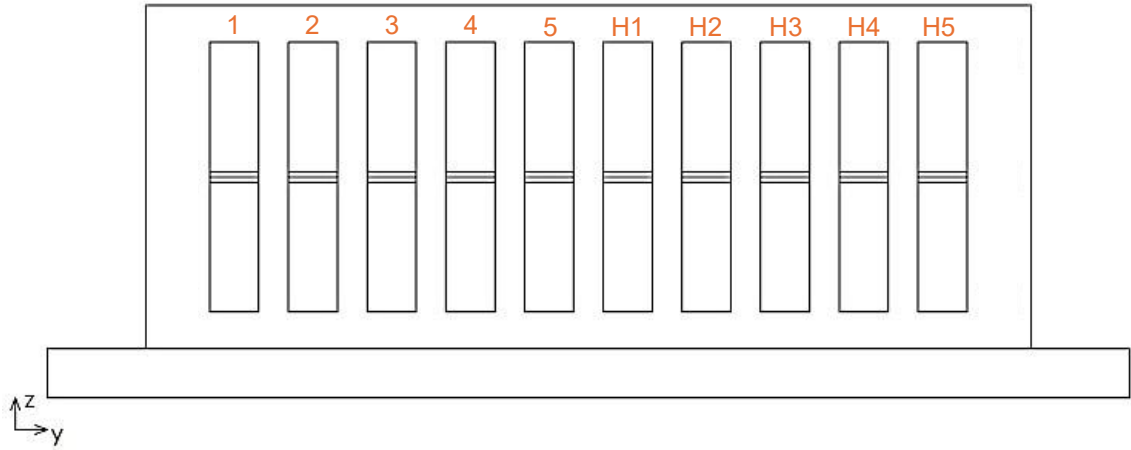


Fig. 4 - Schematic showing the location of the samples extracted from the multi-bead wall. H indicate the samples that will undergo heat treatment.

2.4. Mechanical and Microstructural Characterization

Cross-section samples were embedded in epoxy resin, ground to P2500 with increasingly finer SiC paper, and ultimately polished with 3 μm diamond paste from Buehler. The specimens were then etched through immersion in a 3% Nital solution for 5 s. Optical microscopy was carried out using a Leica DMI 5000M at three regions along the build height (top, middle, and bottom) using magnifications of 50 and 200 μm .

Uniaxial tensile tests were performed at room temperature on a StepLAB EA05 electromechanical testing machine (with a 15 kN load cell) at a displacement rate of 0.017 mm/s. Fracture surfaces from these samples were then examined resorting to Scanning Electron Microscopy (SEM) using a Hitachi SU3800. Dimple dimensions were measured using ImageJ on sets of 10 randomly selected features per specimen.

Vickers microhardness was measured at the mid-height cross-section of the multi-bead thick wall according to ASTM E92 [25] using a Mitutoyo HM-112 Micro-Vickers Hardness Testing Machine with a 1 kgf load applied for 10 s. Six measurements per sample were taken at randomly selected points.

Charpy V-notch impact tests were performed in accordance with EN ISO 148-1:2016 [26]. Specimens from the multi-bead wall were cut, machined to subsize geometry and tested on a pendulum impact machine with 450 J capacity). Five specimens were tested per condition (as-built and aged).

3. Results and discussion

3.1. Response Surface Analysis and Process Optimization

The arc stability computed from the voltage stability in Section 2.2 was used to evaluate the response of the DoE. The ANOVA results for this method, summarized in Table 4, confirms that the regression model is highly significant, with an F-score = 28.18, and a p-value < 0.001, and explains most of the observed variability with $R^2 = 83.5\%$, adjusted $R^2 = 80.6\%$ and predicted $R^2 = 75.6\%$.

Table 4 - ANOVA results for the voltage-amplitude arc stability model

<i>Source</i>	<i>DF</i>	<i>SS (Adj.)</i>	<i>MS (Adj.)</i>	<i>F-Value</i>	<i>P-Value</i>
Model	9	411.36	45.706	28.18	0.0
Linear	3	356.89	188.963	73.34	0.0
Travel Speed (mm/min)	1	5.118	5.118	3.16	0.082
Wire Feed Speed (m/min)	1	148.367	148.367	91.47	0.0
Voltage (V)	1	202.833	202.833	125.04	0.0
Quadratic	3	9.271	3.090	1.91	0.141
Travel Speed ²	1	3.112	3.112	1.92	0.172
Wire Feed Speed ²	1	5.152	5.152	3.18	0.081
Voltage ²	1	0.004	0.004	0.00	0.963
Two-Factor Interaction	3	40.815	13.605	8.39	0.0
Travel Speed × Wire Feed Speed	1	5.413	5.413	3.34	0.074
Travel Speed × Voltage	1	0.191	0.191	0.12	0.733

Wire Feed Speed × Voltage	1	35.212	35.212	21.71	0.0
Error	50	81.105	1.622		
Lack of Fit	6	7.957	1.326	0.80	0.577
Pure Error	44	73.148	1.662		
Total	59	492.460			

Among the individual factors, voltage ($F = 125.04$, $p < 0.001$) and wire feed speed ($F = 91.47$, $p < 0.001$) were the dominant contributors to arc stability, whereas travel speed was not statistically significant ($p = 0.082$). None of the quadratic terms reached significance, indicating that curvature plays a minor role within the explored range. This absence of quadratic terms indicates that the explored process parameter window falls entirely within a somewhat stable short-circuit transfer regime, where arc stability changes monotonically with each parameter. The fitted surface therefore has no internal stationary point, and the predicted optimum falls at the edge of the experimental domain. Therefore, the reported parameter set should be interpreted as the best operating condition within the tested window and broader ranges would be required to capture transitions to other transfer modes and to identify a true global optimum.

The interaction term $WFS \times V$ was also significant ($p < 0.001$), indicating that these two variables must be adjusted in tandem to achieve optimal arc behavior [18]. Higher voltage increases arc length and reduces short-circuit frequency, promoting uniform heat input and smooth droplet detachment [27]. The hierarchy of effects is summarized in the Pareto chart of Fig. 5, where voltage, wire feed speed and their interaction clearly exceed the significance threshold.

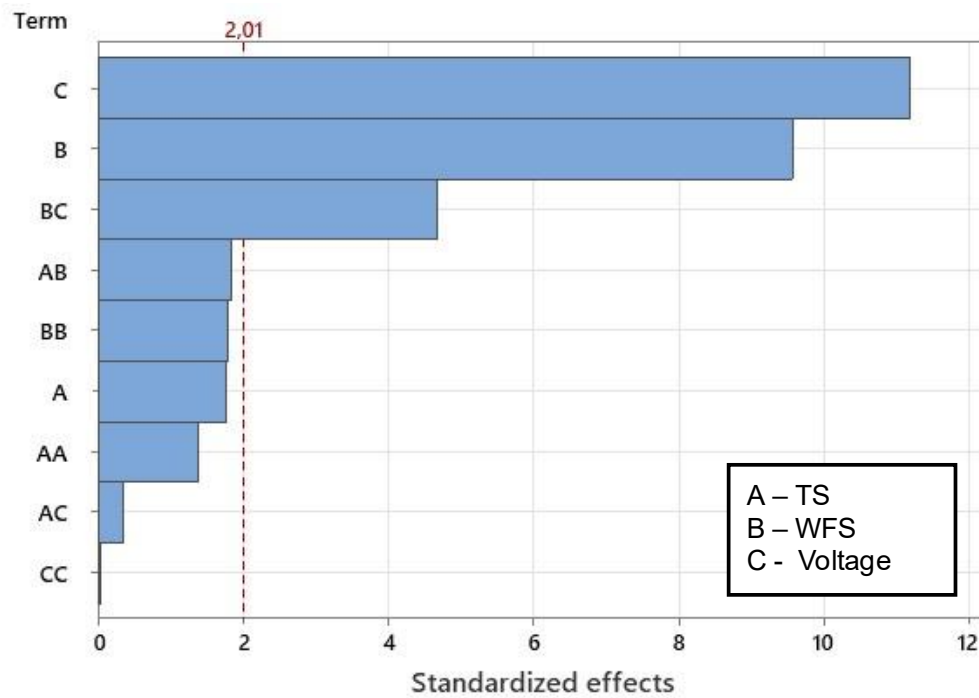


Fig. 5 - Pareto chart of the standardized effects for the voltage-amplitude arc stability model. The dashed red line marks the critical t-value ($|t| \approx 2.01$) for significance at $\alpha = 0.05$.

The residual diagnostics, detailed in Fig. 6, support the statistical assumptions of the model: the normal probability plot shows residuals distributed close to the reference line, the residuals-versus-fitted plot displays no systematic trend or evidence of heteroscedasticity, and the residuals-versus-run-order plot reveals no time-dependent drift, confirming the adequacy of the experimental randomization.

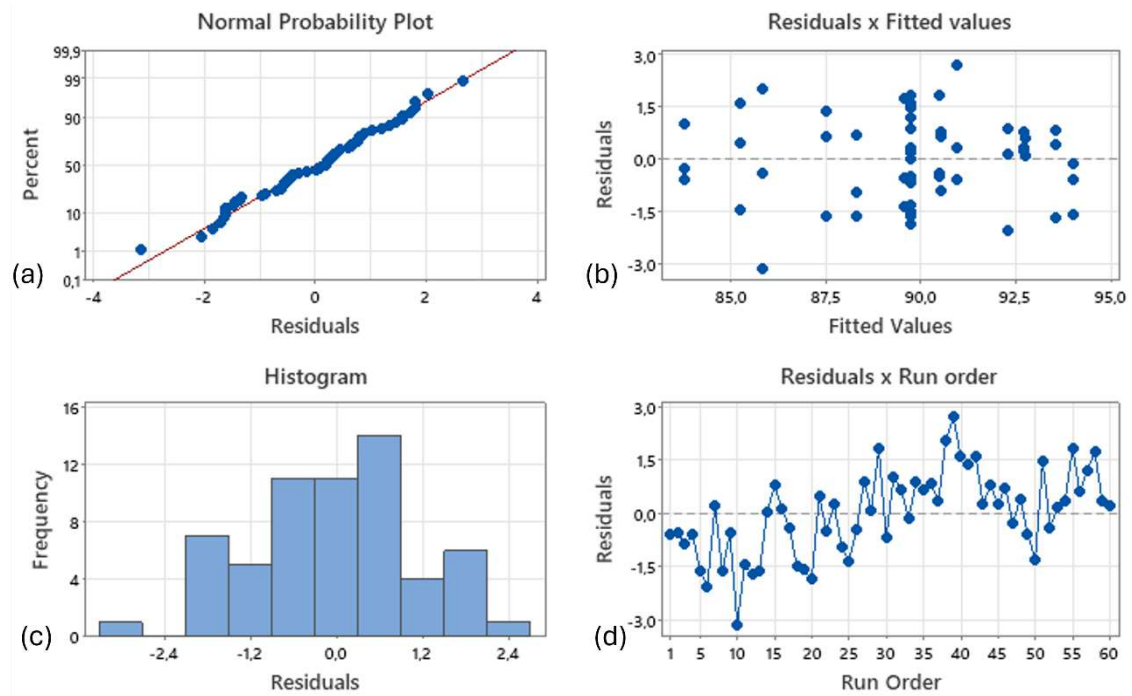


Fig. 6 - Residual plots for the voltage-amplitude arc stability model: (a) normal probability plot, (b) residuals vs fitted values, (c) histogram, (d) residuals vs run order.

The fitted response surfaces, Fig. 7, illustrate the combined influence of the process parameters on arc stability. Stability improves markedly with increasing voltage and WFS, while remaining comparatively insensitive to TS. The WFS–V surface exhibits a pronounced positive gradient, consistent with the significant interaction identified by the ANOVA: at sufficiently high voltage and wire feed speed the arc is adequately powered, reducing arc wandering and stabilizing metal transfer, whereas low combinations of these factors promote irregular short-circuiting and arc instability.

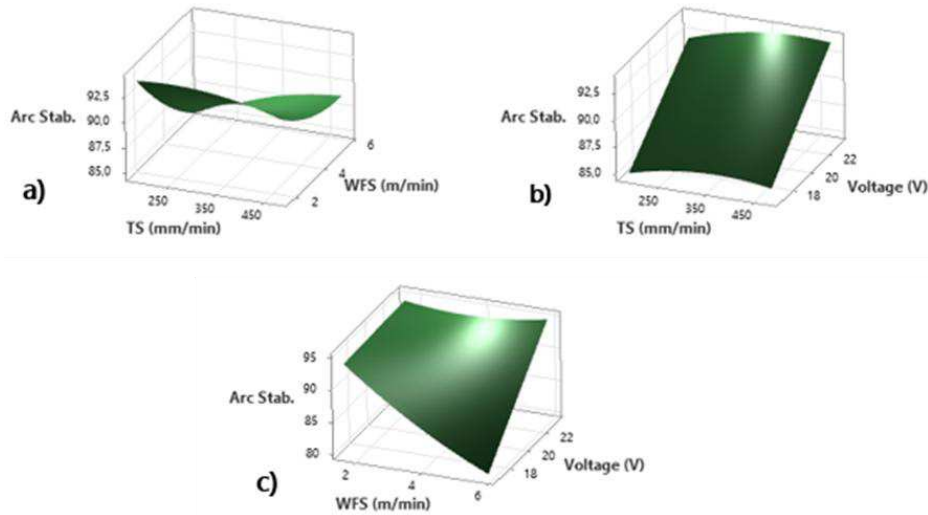


Fig. 7 - Surface Plots of Arc Stability with process variables: a) Effect of TS and WFS on Arc Stability, b) Effect of TS and Voltage on Arc Stability, c) Effect of WFS and Voltage on Arc Stability

Equation 3 presents the fitted second-order polynomial obtained from the response surface regression. Numerical optimization of this model was performed in Minitab using the Response Optimizer tool, with the goal of maximizing arc stability.

$$\text{Arc Stability} = 115.3 + 0.0001 \cdot TS - 14.19 \cdot WFS - 0.78 \cdot V - 0.0000332 \cdot TS^2 + 0.213 \cdot WFS^2 - 0.0022 \cdot V^2 + 0.00422 \cdot TS \cdot WFS + 0.00050 \cdot TS \cdot V + 0.484 \cdot WFS \cdot V \quad (3)$$

The numerical optimization identified the parameter combination that maximizes arc stability, within the studied domain, reported in Table 5. The optimum process parameters (TS $\approx$ 481 mm/min, WFS = 5.9 m/min, V = 23.4 V) yield a predicted arc stability of 96.28, with a 95% confidence interval of [92.99, 99.58], and a composite desirability of 1.000. In practical terms, joint control of WFS and voltage is essential to maximize stability, while travel speed can be treated as a secondary parameter selected to satisfy productivity or geometrical requirements. These optimized parameters were used to produce all the walls already detailed in Section 2.3.

Table 5 - Optimized parameters and predicted arc stability index

TS	WFS	Voltage	Arc Stability (%)
481 mm/min	5.9 m/min	23.4 V	96.3

3.2. Uniaxial tensile testing

Uniaxial tensile specimens were extracted from the thin wall as described in Section 2.3. Table 6 reports UTS and elongation for both build directions in the as-built and aged conditions. In the as-built condition, vertical specimens reached a mean UTS of 1366 MPa with 6.6 % elongation, exceeding the horizontal specimens (1253 MPa, 5.9 %). Direct aging at 480 °C for 5 h produced a substantial improvement in both strength and ductility: UTS rose to 1613 MPa (vertical) and 1687 MPa (horizontal), and elongation increased to 8.5 % and 10.2 %, respectively. Representative stress–strain curves for all conditions are shown in Fig. 8.

The results counter the anisotropy typically reported for AM-built metallic samples, where vertical specimens usually present lower strength than horizontal ones. The conventional explanation is that the loading axis of a vertical specimen is aligned with the build direction, so its gauge length crosses a large number of interlayer boundaries which act as preferential failure regions [4]. Studies on WA-DED processed 18Ni-350 maraging steel have consistently reported the opposite trend where the vertical specimens show higher UTS, YS, and elongation than the horizontal ones [20, 21]. Ge *et al.* [21] attributed this inversion to the preferential alignment of dendrites and intergranular structures along the build direction, which reinforces the material when loaded parallel to that axis and leaves the inter-dendritic regions as preferential weak paths under perpendicular loading.

The strengthening upon aging is commonly attributed to the precipitation of nanoscale intermetallic phases (Ni₃Ti and Mo-rich precipitates) within the tempered martensitic matrix [6, 15], which is also expected to relieve residual stresses while providing precipitation hardening [6, 17]. The concurrent increase in elongation, atypical of conventional precipitation hardening, is consistent with partial relief of residual stresses

and homogenization of microstructural heterogeneity inherited from the as-built state [14, 17]. After aging, horizontal specimens showed higher elongation than vertical ones, indicating that build-direction anisotropy persists: the loading axis of vertical specimens intersects numerous layer boundaries and elongated grains, rendering them more susceptible to localized ductility loss once nanoscale precipitates form [21].

Table 6 - Tensile test results for the WA-DED produced 18Ni-350 maraging steel specimens, composed of three samples per unique condition.

Direction	UTS [MPa]	YS [MPa]	Elongation [%]	Condition
Vertical	1366	500	6.6	As-built
	1613	791	8.5	Aged 480°C/5h
Horizontal	1253	422	5.9	As-built
	1686	782	10.2	Aged 480°C/5h

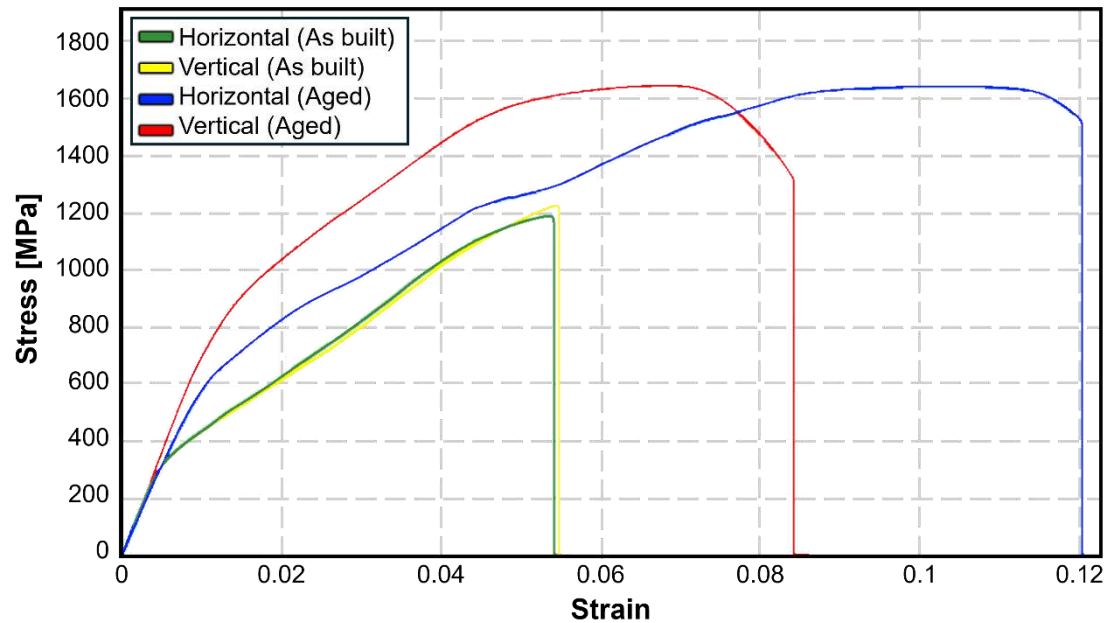


Fig. 8 – Representative engineering stress–strain curves of WA-DED 18Ni-350 maraging steel specimens tested in tension along the vertical and horizontal build directions, in the as-built and aged (480 °C / 5 h / air-cooled) conditions.

3.3. Fractography

The fracture surfaces of the tensile specimens were examined by SEM, with low and high magnification images shown in Fig. 9 and 10, respectively. All specimens exhibited a moderately ductile fracture mode (Fig. 9), characterized by a fully dimpled central region and small, relatively flat shear lips at the periphery, indicating limited but existing plastic deformation before failure, with voids nucleated at inclusions and precipitates acting as stress concentrators [4].

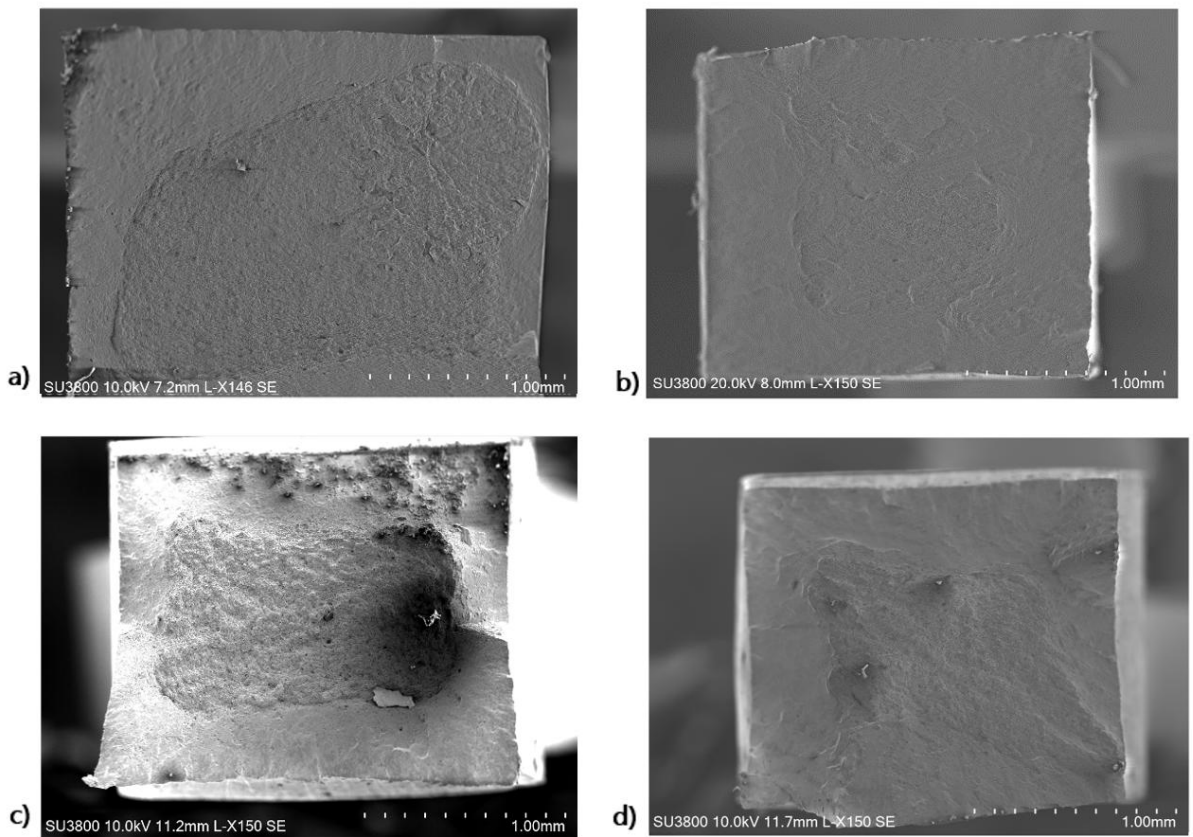


Fig. 9 - Fracture surface of tensile samples at low magnification: a) Vertical (as built), b) Horizontal (as built), c) Vertical (aged), d) Horizontal (aged)

At higher magnification, the as-built horizontal specimen Fig. 10(b) showed shallow and non-uniform dimples with a mean width of $4.2 \pm 0.6 \mu\text{m}$, measured over ten randomly selected dimples using ImageJ. The corresponding aged specimen depicted in Fig. 10(a),

presented a surface dominated by micro-void coalescence with noticeable heterogeneity in dimple size and shape, with dimples that were larger and deeper ($6.1 \pm 0.7 \mu\text{m}$), consistent with the precipitation of intermetallic compounds acting as additional void-nucleation sites [6]. The heterogeneity reflects the absence of a prior solution-annealing step, which would otherwise dissolve segregation and homogenize the matrix before aging [14]. No cleavage planes, river patterns, intergranular cracking, or quasi-cleavage facets were observed in the aged specimen, indicating the absence of severe over-aging or embrittlement.

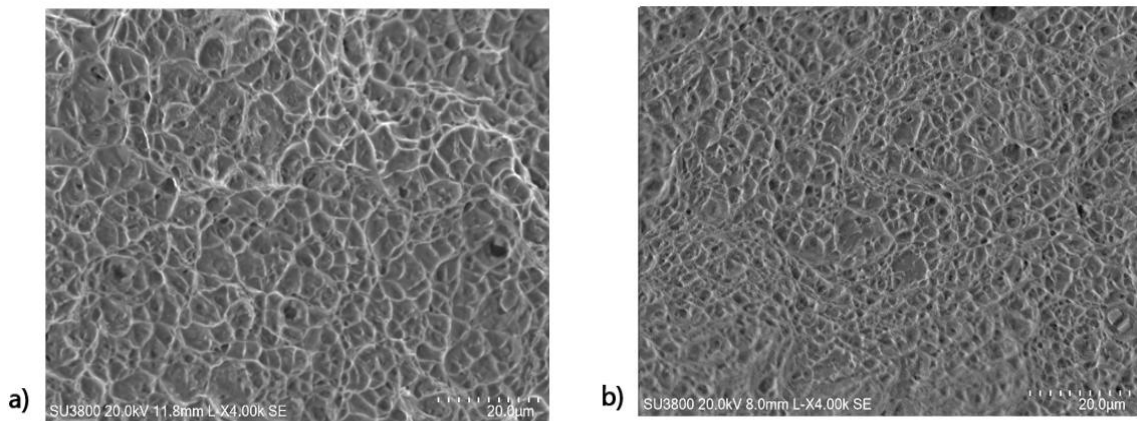


Fig. 10 - Fracture surface of horizontal tensile samples at high magnification: a) Heat treated, b) As Built.

Build-direction effects on the fracture morphology were evident from the comparison of the aged specimens at low magnification, Fig. 9(c-d). In the vertical specimen Fig. 9(c), where the tensile load acts perpendicular to the deposited layers, cracks propagated between the layers along the weaker interlayer boundaries, producing a rougher and more tortuous fracture surface, further amplified by the alignment of columnar grains and residual stress anisotropy, which together promote void nucleation along irregular crack paths [4]. In the horizontal specimen Fig. 9(d), where the load acts parallel to the layers, cracks propagated predominantly along the layers without crossing multiple interfaces, producing a flatter surface and reducing the effect of process-induced anisotropy on fracture behavior [21].

3.4. Microhardness

Vickers microhardness measured at the mid-height cross-section of the multi-bead wall is reported in Table 7. The as-built wall exhibited a mean hardness of 508 ± 10 HV1.0, increasing to 625 ± 9 HV1.0 after aging at 480 °C for 5 h. This ~23 % increase in hardness confirms that direct aging promotes effective precipitation hardening of the martensitic matrix even in the multi-bead configuration. Notably, the as-built hardness of the optimized multi-bead wall is already high relative to values typically obtained only after aging in deposits with fewer beads per layer, supporting the hypothesis that the repeated thermal cycling intrinsic to multi-bead deposition provides a partial in-situ aging effect, discussed in Section Microstructural Characterization.

Table 7 - Vickers microhardness of the multi-bead wall in the as-built and aged conditions.

Condition	Microhardness (HV1.0)
As-built	508 ± 10
Aged (480 °C, 5 h)	625 ± 9

3.5. Impact Toughness (Charpy V-notch)

The Charpy V-notch impact energies of the multi-bead wall are listed in Table 8. The as-built specimens absorbed 438 ± 2 J, while the aged specimens absorbed 440 ± 3 J, rendering a difference below 0.5 %, well within the experimental scatter. Thus, in marked contrast to its effect on hardness, aging had a negligible influence on the impact toughness of the multi-bead material.

Both values approach the nominal capacity of the pendulum machine used (450 J). ASTM E23 and EN ISO 148-1:2016 recommend that reported energies fall between 20

% and 80 % of the machine capacity, since above this range the small residual swing after fracture makes the reading sensitive to friction and windage corrections. The absolute values reported here should therefore be interpreted as lower bounds on the true toughness of the material rather than as accurate measurements. The comparison between conditions remains informative in a qualitative sense: a large aging-induced change in toughness would still have been detectable within the operating range of the machine, and the absence of such a change is consistent with the fracture-controlling microstructural features being established during the multi-bead thermal history rather than during the post-deposition heat treatment. Fractographic inspection of the broken specimens, Fig. 11, showed no major defects in the valid tests, although a few of the porosity- and oxide-related flaws typical of WA-DED were present.

Table 8 - Charpy V-notch impact energy of the multi-bead thick wall (as-built and aged at 480 °C for 5 h).

Condition	Specimen	Impact energy (J)	Average (J)
As-built	1	438	438 ± 2
As-built	2	437	
As-built	3	439	
As-built	4	436	
As-built	5	439	
Aged	H1	442	440 ± 3
Aged	H2	440	
Aged	H3	438	
Aged	H4	442	
Aged	H5	440	

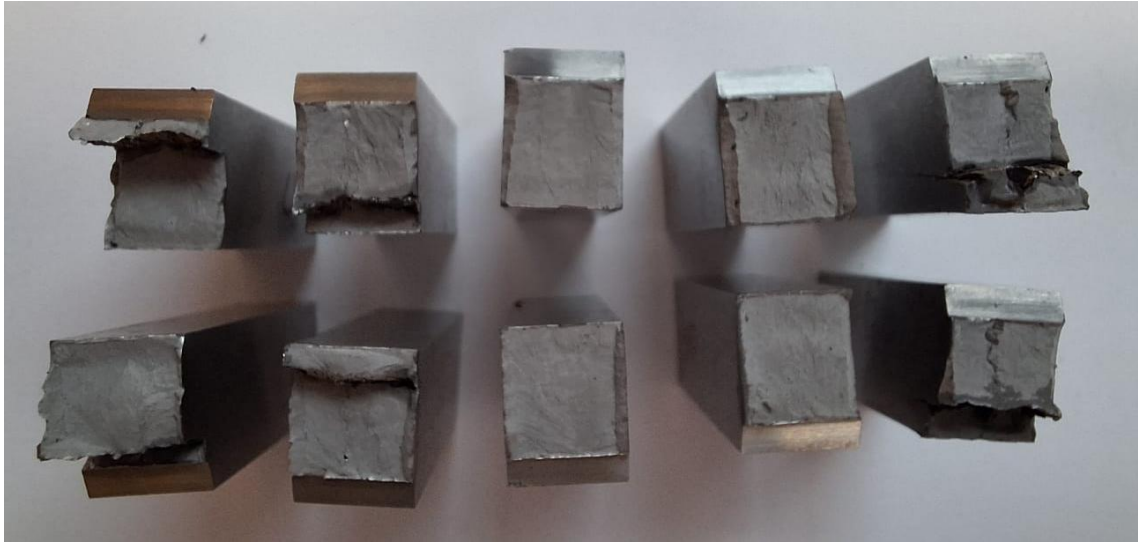


Fig. 11 - Fracture zone on the multi-bead thick wall specimens, as built.

3.6. Microstructural Characterization

Microstructural characterization of the 18Ni-350 maraging steel walls revealed fine, elongated dendritic structures composed predominantly of martensite with small fractions of retained austenite, consistent with prior reports of WA-DED.

The microstructure of the single-bead wall varied systematically along the build height (Fig. 12). The bottom region consisted of coarse columnar grains aligned with the build direction, with a lath-martensite matrix interspersed with pools of reverted/retained austenite at grain boundaries and inter-dendritic regions. The middle region retained columnar, build-aligned grains, but finer and more elongated and with fewer austenite pockets, reflecting the less intense thermal cycling relative to the base. The top region showed a markedly different, less columnar and finer dendritic morphology, an almost fully lath-martensitic matrix and the lowest fraction of retained austenite.

This vertical gradient arises from the thermal history of the DED-Arc process. At the base, repeated reheating from subsequent passes promotes epitaxial grain growth and enriches the inter-dendritic regions in nickel, stabilizing austenite at high temperature and allowing partial reversion upon cooling, which accounts for the coarse grains and higher

austenite fraction. The intensity of reheating decreases towards the middle, while the last-deposited top layers solidify without subsequent remelting, producing the finest and most

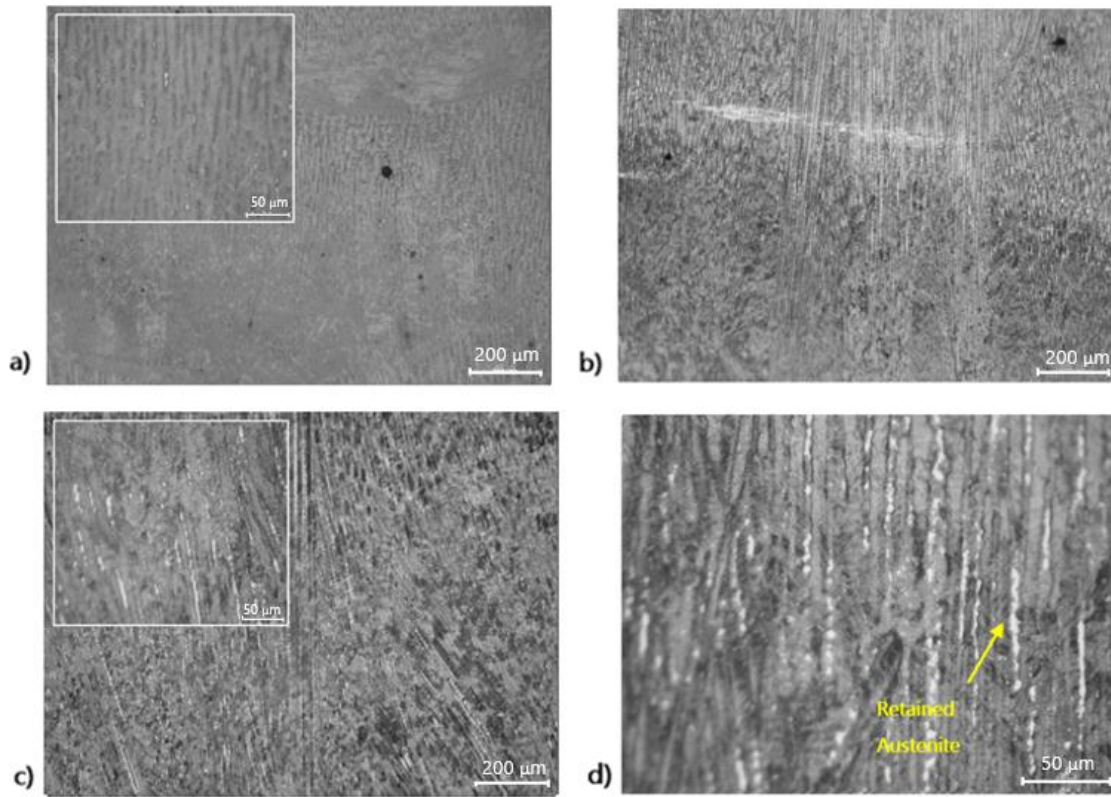


Fig. 12 – Optical imaging of the microstructure of the as-built single-bead WA-DED 18Ni-350 maraging steel at: (a) top (200 μm and 50 μm scale); (b) middle (200 μm); (c) bottom (200 μm and 50 μm); (d) detail of middle region (50 μm).

After direct aging at 480 °C for 5 h (Fig. 13), the microstructure remained predominantly martensitic, but with two distinct features compared to the as-built state. First, the martensite laths appeared coarser, and the fraction of reverted austenite increased, particularly at the bottom and middle regions of the wall, that is, in the locations where the in-deposition thermal cycling had been most intense. Reverted austenite was observed to nucleate preferentially at lath and grain boundaries, visible in detail in Fig. 13d). Second, the cellular grain morphology became more regular and the cellular boundaries thickened, consistent with the tempering of the martensitic matrix and with the diffusion of alloying elements that promotes the formation and coarsening of intermetallic precipitates. The nanoscale strengthening precipitates themselves are not

resolved by optical microscopy, but their presence is inferred from the substantial increase in hardness reported for the aged material and is consistent with prior reports of aged WA-DED maraging steels [28].

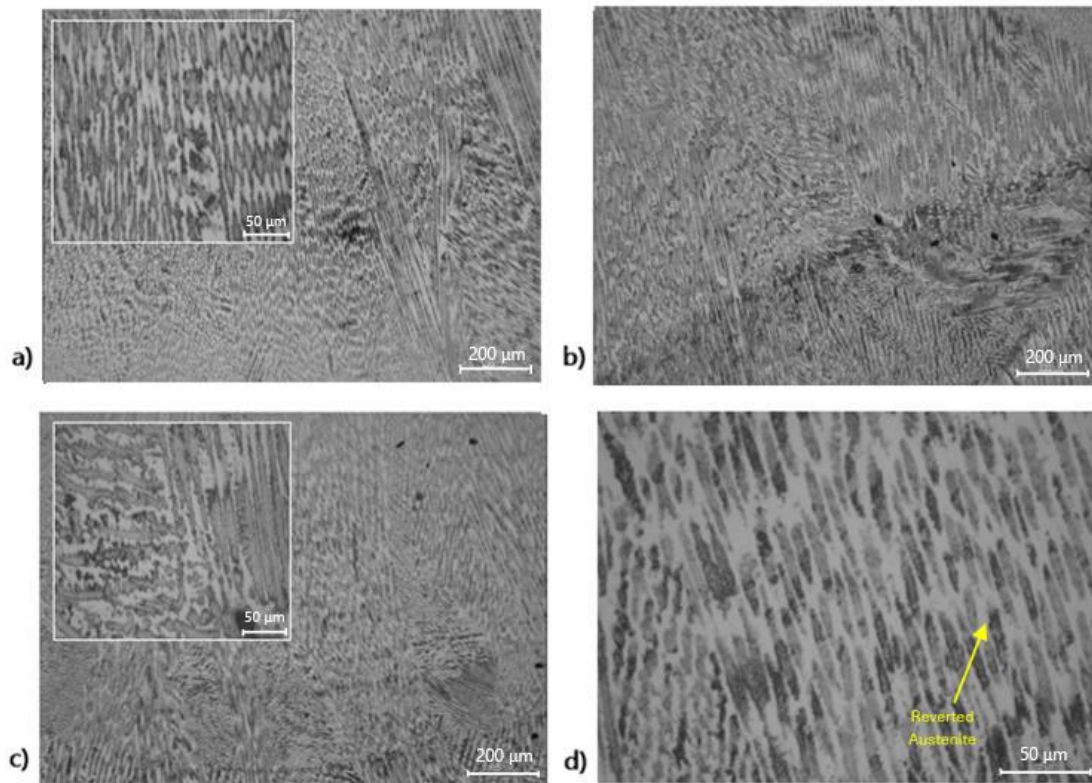


Fig. 13 – Optical micrographs of the aged (480°C/5h, air cooled) single bead WA-DED 18Ni-350 maraging steel wall at: (a) top (200 μm and 50 μm scale); (b) middle (200 μm); (c) bottom (200 μm and 50 μm); (d) detail of middle region showing reverted austenite at lath and grain boundaries (50 μm).

The combination of coarsened laths increased reverted austenite fraction, and the slight enlargement of average grain size indicates that the applied aging condition (480°C/5h) slightly exceeded the peak-aged state for this material, placing the deposit in an incipient over-aged condition. This interpretation is consistent with the simultaneous increase in elongation observed in the tensile data (Section 3.2): in over-aged maraging steels, partial coarsening of the precipitates and the larger fraction of reverted austenite typically reduce peak strength while improving ductility and toughness. The absence of a preceding solution treatment further contributes to the heterogeneity of the aged microstructure,

1 since the inter-dendritic segregation built up during deposition is not erased before
2 precipitation, leading to a non-uniform precipitate distribution.

4 **4. Conclusions**

5 This work established a stable processing window for WA-DED of 18Ni-350 maraging
6 steel deposited under short-circuit transfer using the commercial UTP A 702 feedstock
7 wire and characterized the resulting mechanical and microstructural response in the as-
8 built and post-aged conditions. The main findings are:

9 1) Process optimization. A circumscribed central composite design with 60 runs
10 identified voltage and wire feed speed, together with their interaction, as the dominant
11 factors controlling arc stability, while travel speed acted as a secondary parameter. The
12 maximum predicted arc stability of 96.3% was obtained at $TS = 481$ mm/min,
13 $WFS = 5.9$ m/min and $V = 23.4$ V. The predicted optimum falls at the edge of the tested
14 window and should therefore be interpreted as the best operating condition within the
15 explored short-circuit regime rather than a true global optimum; wider parameter ranges
16 would be required to capture transitions to other transfer modes.

17 2) Tensile behavior of single-bead walls. The optimized parameters produced defect-
18 free single-bead walls with 1366 MPa UTS (vertical) and 1253 MPa (horizontal) in the
19 as-built condition, at 6.6% and 5.9% elongation, respectively. Direct aging at 480°C for
20 5h raised UTS to 1613 MPa (vertical) and 1687 MPa (horizontal) and simultaneously
21 increased elongation to 8.5 % and 10.2 %. These strength levels approach those reported
22 by Kan et al. [15] for solution-treated and aged WA-DED maraging steel (approximately
23 1.7 GPa UTS), indicating that direct aging without a prior solution treatment can deliver
24 a comparable response for this feedstock. The vertical direction retained higher strength
25 than the horizontal one, in line with reports for other WA-DED 18Ni-350 deposits.

3) Multi-bead scale-up. Applying the same optimized deposition parameters in a four-bead-per-layer configuration produced walls with 508 ± 10 HV1.0 in the as-built condition, appreciably above values typically reported for as-built single-bead 18Ni-350 deposits, and 625 ± 9 HV1.0 after aging. The elevated as-built hardness is consistent with a partial in-situ tempering effect associated with the repeated thermal cycling intrinsic to multi-bead deposition.

4) Charpy impact toughness. The multi-bead impact energies of 438 ± 2 J (as-built) and 440 ± 3 J (aged) indicate that direct aging does not measurably affect the impact toughness, in marked contrast to its effect on hardness. Both values approach the nominal capacity of the pendulum machine and should be interpreted as lower bounds on the true toughness of the material; the invariance between conditions nevertheless remains a robust qualitative observation and is consistent with the fracture-controlling microstructural features being established during the multi-bead thermal history rather than during post-deposition aging.

5) Microstructure. The single-bead walls exhibited a vertical gradient of columnar grain size and retained/reverted austenite fraction consistent with the thermal history of the deposition. After aging, martensite laths coarsened and the reverted austenite fraction increased, particularly at the bottom and middle regions, consistent with an incipient over-aged state.

Overall, the combination of process optimization, single-bead property characterization and multi-bead scale-up demonstration supports the viability of WADED as a route to near-net-shape 18Ni-350 maraging steel components with high hardness and impact tolerance. Future work should extend the parameter window beyond the current short-circuit regime to identify a true global optimum, incorporate SEM/EBSD and XRD characterization to quantify precipitate volume fractions and

1 reverted austenite content in both single-bead and multi-bead walls, and evaluate the
2 effect of a preceding solution treatment on the multi-bead thermal-mechanical response.
3 Fatigue testing of the multi-bead configuration under conditions representative of tooling
4 applications would further clarify the trade-off between the in-situ tempering effect and
5 defect-driven fatigue failure.

6

7

8

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12
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