

A sensitivity workflow for interlayer dwell-time screening in sparse open WAAM data

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Abstract

Interlayer dwell time in wire arc additive manufacturing (WAAM) is often treated as a single process threshold, but sparse datasets can support different limits depending on the indicator and analysis. We reanalysed twelve single-pass multilayer walls—six ER70S-6 and six ER110S-G—with one wall at each of six nominal dwell conditions from 0 to 240 s. Geometry, radiographic classification and hardness were traced to their released records. We evaluated geometric recovery under alternative criteria, saturation laws, leave-one-out deletion and 0.1 mm height quantisation. The first tested dwell satisfying the illustrative criteria ranged from 30 to 240 s, with one fitted crossing beyond the tested range; the rounding analysis did not change this overall range. Both alloys completed about three-quarters of their observed geometric change by 30 s. ER70S-6 cap-region means showed no clear plateau, but the 120–240 s difference is cumulative over a 120 s interval and includes one endpoint wall. Radiographic classification showed no monotonic ordering with dwell. The data therefore support a sensitivity-based screening workflow, not a unique process boundary: geometry, radiography and hardness should remain separate evidence streams until repeated builds and qualified acceptance criteria are available.

1 Introduction

WAAM deposits weld beads layer by layer at high deposition rates [1]. Thermal management is central: as the wall grows, heat accumulates, and interlayer dwell time is a primary process variable controlling the local thermal history and the interpass temperature at which each new layer is deposited.

Dwell time places the process between two thermal limits. Short dwell allows heat to accumulate, which can enlarge the melt pool and promote excessive remelting, leaving the wall short, wide or bulged; fusion is not expected to be limiting here, but geometric accuracy and process stability can deteriorate. At the opposite limit, insufficient reheating of the previous layer can produce interlayer lack of fusion or cold lap. Longer dwell is treated here only as a possible cooling-related route towards that limit, and not as a threshold established by the available 0–240 s data [2]. Remelting depth links the two regimes physically, since excess remelting at short dwell can drive slumping while insufficient remelting at long dwell can drive lack of fusion; it is neither measured nor modelled in this study.

Arc-based WAAM studies have established that dwell time and interpass cooling affect residual stress, distortion, microstructure, hardness and geometric quality [2–9]. Interlayer delay and interlayer cooling change microstructure, wall shape and bead geometry in low-carbon and austenitic steels [10–13], and interpass temperature and thermal cycling govern the transformation product and hardness of high-strength deposits [14–17], the wire class of the ER110S-G walls analysed here. Independent ER110S-G walls have been used for microstructure-estimation studies [18], and wire-laser directed energy deposition (DED) supplies related thermal-modelling context [19], but neither belongs to the AIMEN/PIONEER dwell sweep. Together these studies establish dwell as a practical thermal-history variable. Almost all of them, however, rest on newly produced specimens, and none provides a calibrated remelting-depth threshold for the dataset analysed here.

Four studies are particularly relevant. Turgut et al. [4] varied dwell in WAAM of low-carbon low-alloy steel and reported effects on output quality; Nagasai et al. [10] examined the effect of interlayer delay on microstructure and bead geometry in low-carbon steel; and Mattera et al. [6] compared interlayer cooling strategies for ER70S-6, reporting layer geometry, microstructure, hardness and corrosion response. All three used purpose-built specimens and reported new property measurements. The closest methodological precedent is Tzimanis et al. [20], who developed process windows for wire directed energy deposition by defining reference geometries and deriving acceptance thresholds from metrological responses; that work addressed a laser-based process in AISI 316L and used purpose-built qualification experiments.

Open manufacturing datasets are increasingly available, but they rarely provide enough independent replication or harmonised measurements to show which engineering claims are identifiable. This study reanalyses the AIMEN/PIONEER WAAM dwell-time dataset to address that gap, rather than to identify an optimum dwell time for these walls. It makes three contributions: a traceable workflow for extracting and checking open manufacturing records; a sensitivity analysis showing how criteria, response models, leave-one-out deletion and measurement resolution alter a geometric bound; and an evidence-boundary analysis that keeps geometry, radiography and hardness separate when they do not define the same quality response. The workflow is demonstrated on the AIMEN/PIONEER walls and is intended for sparse manufacturing datasets more generally.

The analysis uses a dataset produced by AIMEN Technology Centre with Fraunhofer SCAI and EBBAMS and released through the EU PIONEER project under CC BY 4.0 [21]. It contains geometry, monitoring, non-destructive testing (NDT) and destructive-testing records for ER70S-6 and ER110S-G dwell sweeps. All analyses below rely on these released records.

2 Materials and dataset

2.1 Specimens and process

Single-pass multilayer walls were deposited on a $250 \times 150 \times 12$ mm baseplate clamped at four corners; the nominal CAD wall is 185 mm long. The process used 1.2 mm wire at a feed of 4 m/min. M1 denotes ER70S-6 (Böhler QG3, low-carbon steel; 32 layers) and M2 denotes ER110S-G (Union X85, high-strength steel; 27 layers); the release does not document why the layer counts differ. Within each alloy, dwell time is the varied process parameter. The released record confirms constant current and voltage across the dwell sweep, so no multivariate heat-input regression was attempted. Two electrical records are available: the as-built AutomationML (AML) values (M1 131 A / 13.4 V; M2 137 A / 14.1 V) and the computer-aided engineering (CAE) frame simplification (136 A / 13.6 V / 8.2 mm/s for both alloys).

The manufacturing workbook lists inconsistent travel-speed fields of 10 and 50 mm/s, while the CAE frame uses 8.2 mm/s. A coarse wire-volume check using the released wire size, feed rate and height $\times$ penetrated-thickness proxy strongly disfavors 50 mm/s but cannot distinguish 8.2 from 10 mm/s

because bead shape, transfer efficiency and the executed path are unavailable (Supplementary Table S13). The 10 mm/s field is retained in the supplementary rank-only thermal calculation. The records specify one bead per layer but not oscillation or deposition direction.

2.2 Dwell sweep

The released dataset contains cases labelled 0, 30, 60, 90, 120 and 240 s per alloy, where 0 s denotes continuous deposition. The Zenodo landing-page description lists dwell times of 30–240 s, but the released directory also holds continuous-deposition cases labelled M1_0 and M2_0. These serve here only as experimental lower-bound anchors; the reduced thermal model covers 30–240 s. Supplementary Table S1 maps every extracted value, including the 0 s cases, to its source file.

2.3 Reference observations and measurement resolution

Reference observations comprise geometry (wall height and average layer height) from metrology; the reported radiographic classification, assessed by the data originators against quality level B of UNE-EN ISO 5817:2023 [22]; macrographs (Nital 10%, UNE-EN ISO 17639:2022 [23]); micrographs at three wall heights; and Vickers hardness (HV0.3, UNE-EN ISO 6507-1:2024 [24]). Surface two-camera imaging and the consortium finite-element (FEM) and VMAP-standard outputs—the latter a vendor-neutral CAE data-transfer format—serve only as contextual cross-references, not as primary validation targets. The monitoring stream of this pilot line has already been analysed by the data originators, who correlated the electrical signal with the contact-tip-to-work distance recorded by the welding camera [25]; that modality is not revisited here.

Measurement resolution constrains the geometric analysis. The released metrology workbook describes wall height as manually measured, quotes it to 0.1 mm, and calculates average layer height as wall height divided by the deposited layer count (32 for ER70S-6, 27 for ER110S-G). Average layer height is therefore derived and adds no information independent of wall height; its quantisation step is 0.0031 mm for ER70S-6 and 0.0037 mm for ER110S-G. No metrology uncertainty is stated. These increments describe the numerical resolution of the released values, not measurement uncertainty.

Two further measured quantities are available. The radiographic certificates state a penetrated thickness for each ER70S-6 wall, quoted to 0.5 mm. This is an independent geometric observation that does not derive from the wall-height record, but it is an exposure-planning field rather than a metrology result: the certificates list a digital caliper, a tape measure and a steel rule among the equipment without stating which was used, and one value is given per wall. It is used below as a coarse corroboration of the height trend, not as a second precision measurement.

The monitoring workbooks also contain a high-frequency baseplate thermocouple channel (T3). Four ER70S-6 workbooks (30, 60, 90 and 240 s) yielded at least four intervals between detected peaks; M1_0 and M1_120 lack usable T3 channels. The detected intervals were not registered to deposited-layer numbers and some span missed thermal cycles. T3 is therefore retained only as an unregistered source-level diagnostic (Supplementary Tables S4 and S7), not as wall interpass temperature.

Hardness is the one modality with repeated within-wall measurements. The released report (AIMEN order 1164109) describes six transverse sections from six ER70S-6 walls—one section per wall—and lists individual values along two indentation tracks, labelled 1 and 2, on each section. Each wall contributes 42–62 indentations in total. The rows are labelled Inf and Sup, but the report provides neither indentation spacing nor metric coordinates. It states an expanded measurement uncertainty of 6.7% at $k = 2$, about ± 13 HV0.3 on a single indentation near 190 HV0.3. All conditions were indented on the same instrument on the same test date, so some systematic components may be shared; the covariance needed to quantify their cancellation in differences between condition-level means is unavailable.

2.4 Dataset scope and known gaps

ER110S-G hardness is absent: both released hardness folders contain the same ER70S-6 report and M1-labelled images. Hardness analysis is therefore restricted to ER70S-6, with no cross-alloy comparison.

The radiographic records of the two alloys are not equally traceable. Both sets are reported on the same certificate form and name a Level 2 evaluator. The ER70S-6 certificates identify the alloy and label each exposure row with its specimen, whereas on the ER110S-G certificates the specimen is identified by the released file name rather than within the document. Cross-alloy radiographic comparisons are therefore treated as indicative only.

Two corrections were applied to the ER70S-6 hardness report. Merged source cells that would otherwise duplicate the first indentation of each row were counted once, and one probable transcription duplicate in the 30 s root-region data was excluded. The latter changed the corresponding wall-level value by 0.2 HV0.3 and did not affect the conclusions. Row-level provenance is given in Supplementary Tables S1 and S8.

3 Methods

The workflow comprises four stages: provenance audit, indicator-role assignment, bound construction from observed and fitted responses, and sensitivity testing of criteria, model form, anchor selection and measurement resolution. Sections 3.1–3.7 implement these stages for the released WAAM dataset.

3.1 Quality-indicator separation

The evidence sources are assigned separate roles in the screening interpretation. Radiographic classification describes the reported internal-inspection category, while geometric stability is described by average layer height, wall height and macro shape. The released metallographic reports describe microstructure collectively but do not provide wall-level lack-of-fusion classifications; no such verdict was therefore inferred from the section images. Hardness is an ER70S-6 property response measured along two indentation tracks on one released transverse section per wall and is the only source carrying repeated within-wall measurements. The reduced thermal calculation provides an exploratory ordering check; it does not set a boundary.

3.2 Height-recovery kinetics

We use the following height-recovery law for average layer height as a geometric response descriptor, not as a process-qualification model:

$$h(t_d) = h_0 + \Delta h_{\infty} [1 - \exp(-t_d/\tau_h)] .$$

Here, h_0 is the fitted zero-dwell average layer height, Δh_{∞} is the recoverable average-layer-height change and τ_h is the dataset-specific recovery time scale. The time scale is an empirical descriptor on the nominal-dwell axis; it is neither a measured thermal time constant nor a transferable material or process parameter. Because no condition was sampled between 0 and 30 s, the response shape within that interval is model-dependent. Within each alloy, fitting wall height gives the same time scale because average layer height is a constant rescaling by layer count. We distinguish observed from fitted recovery. The observed fraction is $gobs(t_d) = [hobs(t_d) - hobs(0)] / [hobs(240) - hobs(0)]$; at 30 s it is 71.6% for ER70S-6 and 73.8% for ER110S-G. The fitted fraction is $gfit(t_d) = 1 - \exp(-t_d/\tau_h)$, with criterion crossing time $t_x = -\tau_h \ln(1 - x)$. We report $x = 0.60, 0.70, 0.80$ and 0.90 . The first tested dwell at or above each criterion crossing time is the grid-rounded geometric screening bound. These recovery fractions are illustrative sensitivity levels rather than externally qualified engineering acceptance criteria.

3.3 Functional-form and criterion sensitivity

The criterion sensitivity follows directly from the crossing expressions: $\partial t_x / \partial x = \tau_h / (1 - x)$ for the exponential law and $\partial t_x / \partial x = \tau_h / (1 - x)^2$ for the hyperbolic law; moving from 0.60 to 0.90 therefore increases sensitivity fourfold and sixteenfold, respectively. Model-form sensitivity was assessed with the hyperbolic law $h(t) = h_0 + \Delta h_{\infty} t / (t + \tau_h)$, a linear non-saturating reference and a grid-only rule. The grid-only rule applies $gobs$ and normalises to $hobs(240)$, whereas the fitted laws apply $gfit$ and normalise to their fitted asymptotes. Each point was deleted in turn and the models refitted in a leave-one-out (LOO) analysis; deleting 0 s makes its held-out prediction an extrapolation, whereas deleting an intermediate point makes its held-out prediction an interpolation. The LOO held-out RMSE is the root mean square of the six held-out residuals, not the RMSE of the five-point refits. The fits constrained h_0 and Δh_{∞} to be non-negative and τ_h to be positive. Bound-hitting fits were retained as sensitivity outcomes but not interpreted physically; the imposed bounds, fitting settings and all refits are reported in Supplementary Table S11. The corrected Akaike information criterion (AICc) was not used to choose between the equal-parameter saturation laws; with six observations, LOO more directly addresses sensitivity to one omitted condition.

Rounding-interval sensitivity was assessed separately from measurement uncertainty. Each wall height was perturbed to the lower endpoint, midpoint and upper endpoint of its ± 0.05 mm rounding interval, giving $3^6 = 729$ deterministic combinations per alloy. The models and grid-only rule were recomputed for each combination; Supplementary Table S11 reports the resulting time constants, criterion crossing times and tested-grid bounds. These are not confidence intervals.

3.4 Interpretation of the response measures

We compared geometry, radiographic classification and hardness by alloy and dwell condition. Geometry provided a tested-grid bound, while the model comparison and leave-one-out analysis of Section 3.3 assessed how far that bound could move. Radiography described only the tested range reported as accepted. The range closes when a longer tested dwell is rejected; if no rejection occurs, its upper end remains right-censored within the tested domain. A rejection at one condition was not treated as a failure threshold because it rests on a single wall. The metallographic report scope and thermal index were retained as context: the former supplies no wall-level fusion verdict, and the latter was neither independently calibrated nor repeated across builds.

3.5 Dataset extraction and provenance of the radiographic labels

We extracted geometry, radiographic classification, macrograph observations and ER70S-6 hardness values from the AIMEN/PIONEER WAAM repository [21]. Average layer height was taken from the metrology workbook, and wall thickness from the penetrated-thickness field of the radiographic certificates. The terms “accepted” and “rejected” reproduce the classification in the released inspection reports and do not represent an independent re-evaluation.

Radiography followed UNE-EN ISO 17636-1:2023 [26] at test level B, with acceptance level 1 of UNE-EN ISO 10675-1:2022 [27] and quality level B of UNE-EN ISO 5817:2023 [22], the most stringent of the three levels in that standard. The required image-quality sensitivity was met or exceeded on every exposure. Supplementary Table S9 lists the exposure, film and image-quality parameters transcribed from the certificates. For ER70S-6, evaluation was reported on accredited certificates by a named Level 2 operator; the ER110S-G forms use the same reporting structure but do not identify the specimen internally, as detailed in Section 2.4. The present study transcribes the reported classification without re-reading the films. Radiographic detectability in WAAM deposits is technique-dependent and finite [28, 29]. An absent indication is therefore not equivalent to an absent defect, and a rejection at level B does not imply rejection at level C or D.

The certificates record indications by the numbered categories of the reporting procedure, in which 2 denotes porosity, 3 denotes clustered porosity and 11 denotes lack of fusion. For the ordinal analysis in Section 4.3 the released outcome is mapped to three levels: 2 for accepted with no indication, 1 for accepted with a porosity indication, and 0 for rejected. The mapping transcribes the released category and introduces no re-assessment. The scale encodes ordinal classification alone and implies no equal severity spacing between categories, so it is used with rank statistics only.

The release is not internally consistent, so one provenance rule is needed. Besides the certificates, the dataset contains a summary workbook that repeats the radiographic classification for each wall, and for ER110S-G that workbook disagrees with them: it records porosity indications at 60, 90 and 120 s and none at 240 s, whereas the certificates record no indication at 60 and 120 s and a porosity indication at 90 and 240 s. The ER70S-6 entries agree. Where the summary workbook and the condition-specific radiographic forms disagree, we use the latter as the primary inspection record, because they retain the

exposure technique and the condition-level indication categories. For ER110S-G the specimen is not identified within the certificate itself, which remains a provenance limitation, so the resulting comparisons are treated as indicative only. We note the discrepancy so that readers reconciling this paper against the summary workbook are not misled.

3.6 Exploratory thermal consistency check

An exploratory reduced thermal calculation reproduced the ER70S-6 dwell ordering, but a dwell-only baseline did so as well. Because absolute temperature was neither mesh-converged nor experimentally calibrated, the calculation was not used to infer a cooling time scale, interpret τ_0 or select a screening bound. For the T3 diagnostic, the channel was binned at 0.5 s, peaks were detected with 8°C prominence and 4 s minimum separation, and the minimum within each interval between consecutive detected peaks was recorded. These between-peak minima were not assigned to deposited-layer numbers; pre-layer temperature is therefore not inferred. Implementation and verification details are confined to Supplementary Tables S2–S7 and S12.

3.7 Statistical handling

Each alloy–dwell condition contains one wall, so the analysis describes the tested conditions rather than a population effect. Spearman rank coefficients use mid-ranks where responses tie; exact two-sided permutation values are reported in Supplementary Table S10. The same convention applies to the six-condition ordinal radiographic score and to the four-condition, unregistered T3 diagnostic in Supplementary Table S7. These coefficients summarise ordering and are not a set of confirmatory tests.

Hardness condition-level means are compared through their difference and through the two indentation-track means on the single released cross-section of each wall. The design is nested, not replicated: indentations sit within tracks and one wall represents each condition, so no population-level confidence interval is reported for a between-condition difference.

4 Results

4.1 Dwell-dependent geometry

Table 1 summarises the reference observations extracted from the release, and Fig. 1 plots the height response against dwell.

Table 1

Experimental reference observations extracted from the public dataset [21]. Average layer height is wall height divided by the deposited layer count and is therefore a derived quantity; the thickness entry is the penetrated thickness stated on the radiographic certificates. RT indication codes follow the reporting procedure: 2 = porosity, 3 = clustered porosity. ER110S-G thickness is reported only as a range covering all conditions. Recovery fractions quoted in the text are computed from the underlying wall-height values before division by the layer count and rounding.

Specimen (alloy)	Dwell (s)	Wall height (mm)	RT penetrated thickness (mm)	Avg layer height (mm)	RT indication	RT result	Macro shape
M1_0 (ER70S-6)	0	39.8	9.0	1.244	2, 3	Rejected	short, bulged, slumped
M1_30 (ER70S-6)	30	47.6	7.0	1.488	none	Accepted	tall, straight
M1_60 (ER70S-6)	60	49.0	6.5	1.531	2	Accepted	tall, straight
M1_90 (ER70S-6)	90	49.2	6.5	1.538	2	Accepted	tall, straight
M1_120 (ER70S-6)	120	49.8	6.5	1.556	2	Accepted	tall, straight
M1_240 (ER70S-6)	240	50.7	6.5	1.584	2, 3	Rejected	tall, straight; late-layer instability noted
M2_0 (ER110S-G)	0	38.5	7–9	1.426	none	Accepted	short, bulged, slumped
M2_30 (ER110S-G)	30	44.7	7–9	1.656	none	Accepted	tall, straight
M2_60 (ER110S-G)	60	46.3	7–9	1.715	none	Accepted	tall, straight
M2_90 (ER110S-G)	90	46.0	7–9	1.704	2	Accepted	tall, straight
M2_120 (ER110S-G)	120	46.4	7–9	1.719	none	Accepted	tall, straight
M2_240 (ER110S-G)	240	46.9	7–9	1.737	2	Accepted	tall, straight

For M1_240, “late-layer instability” refers to the released inspection and macrograph record and is not treated as a radiographic discontinuity category.

Average layer height increases from 1.244 to 1.584 mm for ER70S-6 over 0–240 s. For ER110S-G it rises and saturates from 1.426 to 1.737 mm, though not strictly monotonically: the 90 s value falls slightly below the 60 s value. That difference is 0.011 mm, or 0.3 mm of wall height (three quantisation steps of the released record), and because the release reports no measurement uncertainty, the significance of the local inversion cannot be determined. The largest change occurs between 0 and 30 s in both alloys, consistent with reduced heat-accumulation-driven slumping once dwell is introduced (Fig. 1). No experimental error bars are shown, since the dataset provides one wall per condition.

The radiographic certificates provide an independent geometric observation for ER70S-6: penetrated thickness decreases from 9.0 mm at 0 s to 7.0 mm at 30 s and 6.5 mm at longer dwell (Table 1). It varies inversely with both dwell and wall height (Spearman $\rho = -0.85$ for each; $p = 0.067$ for both) and is constant at the reported 0.5 mm resolution from 60 s onwards. With one local value per wall and three distinct values, this is directional evidence rather than a precision curve. The cross-sectional-area check is in Supplementary Table S13; ER110S-G thickness is reported only as a 7–9 mm range and is not used.

4.2 Height-recovery fit, model comparison and sensitivity

The full-data exponential fits give $\tau_h = 22.2$ s for ER70S-6 and 20.2 s for ER110S-G. Across the 30–240 s conditions, ER70S-6 average layer height increased monotonically with dwell ($\rho = +1.00$). These are condition-level patterns from one wall per condition. Table 2 compares the candidate laws and the leave-one-out sensitivity of the fitted descriptor and held-out prediction error.

Table 2

Fit comparison and leave-one-out sensitivity of the average-layer-height recovery descriptor. LOO held-out RMSE is calculated from the six omitted-point predictions; “–” denotes that the linear reference has no time constant. Reported decimals are numerical fit outputs, not uncertainty estimates.

Alloy	Model	τ_h (s)	RMSE (mm)	LOO τ_h range (s)	LOO held-out RMSE (mm)
ER70S-6	Exponential	22.2	0.0131	18.9–79.8	0.0865
ER70S-6	Hyperbolic	14.0	0.0059	11.6–53.3	0.0711
ER70S-6	Linear	–	0.0811	–	0.1675
ER110S-G	Exponential	20.2	0.0092	18.6–28.8	0.0448
ER110S-G	Hyperbolic	11.4	0.0083	1.6–12.7	0.5823
ER110S-G	Linear	–	0.0804	–	0.1651

Both saturation laws fitted the six observations better in-sample than the linear reference. The hyperbolic law gave slightly lower full-data RMSE, but its ER110S-G refit reached the imposed lower bound $h_0 = 0$ mm when the 0 s point was deleted; its held-out RMSE was 0.5823 mm, above the full observed

response range of 0.311 mm. Deleting the 0 s anchor increased the exponential τ_{ex} from 22.2 to 79.8 s for ER70S-6 and from 20.2 to 28.8 s for ER110S-G; the corresponding ER110S-G hyperbolic fit gave $\tau_{\text{hy}} = 1.6$ s. For ER70S-6, the 0 s-deleted exponential fit moved the 60%, 70%, 80% and 90% tested-grid bounds to 90, 120, 240 and 240 s. Thus the 30 s lower end depends on treating the collapsed 0 s wall as part of the same smooth response. These outcomes are structural sensitivity checks, not physical time constants; all refits are in Supplementary Table S11.

The two saturation laws agreed at the 60% and 80% criteria, giving tested-grid bounds of 30 and 60 s, respectively. They diverged at 70% and especially 90%, where the full-data results extended to 240 s. The grid-only rule placed the ER70S-6 90% bound at 120 s. Across the criterion, model and deletion choices, the tested-grid results ranged from 30 to 240 s, with one crossing beyond the tested range.

Across the 729 rounding-interval perturbations per alloy, every full-data tested-grid bound was unchanged except the ER70S-6 hyperbolic 90% result, which shifted between 120 and 240 s; the overall 30–240 s sensitivity conclusion was unchanged (Supplementary Table S11).

Table 3

Criterion crossing times and tested-grid bounds under the two saturation laws, using the full-data time constants of Table 2. The tested-grid bound is the first tested dwell at or above the criterion crossing time. Crossings below 30 s are model interpolations within the tested 0–240 s domain but lie in the unsampled interval between the 0 and 30 s conditions; they are not experimentally resolved transition times. Crossing times use the unrounded fitted time constants, which Table 2 displays to one decimal; that precision reflects the fit, not the 0.1 mm resolution of the wall-height record.

Alloy	Criterion x	Exponential t_x (s)	Exponential screening bound (s)	Hyperbolic t_x (s)	Hyperbolic screening bound (s)	Grid-only screening bound (s)
ER70S-6	0.60	20.4	30	20.9	30	30
ER70S-6	0.70	26.8	30	32.6	60	30
ER70S-6	0.80	35.8	60	55.8	60	60
ER70S-6	0.90	51.2	60	125.6	240	120
ER110S-G	0.60	18.5	30	17.1	30	30
ER110S-G	0.70	24.3	30	26.5	30	30
ER110S-G	0.80	32.5	60	45.5	60	60
ER110S-G	0.90	46.5	60	102.4	120	60

4.3 No resolvable dwell ordering in the radiographic classification

The quality indicators do not point to one common dwell interval.

ER70S-6 is radiographically rejected at 0 and 240 s and accepted from 30 to 120 s. ER110S-G is accepted at all tested dwell times, although its 0 s condition is geometrically short and bulged. On the three-level ordinal scale of Section 3.5, ER70S-6 runs 0, 2, 1, 1, 1, 0 across 0 to 240 s and ER110S-G runs 2, 2, 2, 1, 2, 1. Neither sequence is monotonic in dwell: the rank correlations are -0.19 and -0.62 , respectively; exact permutation values are in Supplementary Table S10. Radiography therefore does not establish a common dwell ordering. With six conditions, three levels and repeated ties, the rank summaries are descriptive rather than confirmatory.

The ER70S-6 rejections at 0 and 240 s both carried categories 2 and 3; accepted walls carried at most category 2. Clustered porosity therefore set the observed accepted range, but its occurrence at both extremes, absence at intermediate conditions and acceptance of ER110S-G at 240 s do not support a dwell effect. The 240 s result is treated as a one-wall boundary observation; repeat builds and indication dimensions would be needed to infer more.

No category-11 lack-of-fusion indication was reported in any of the 12 released radiographic certificate rows. The metallographic reports do not provide wall-level lack-of-fusion classifications, so the section-image set is not used to claim per-wall or whole-wall absence. Endpoint macrographs in Fig. 2 support the short-dwell slumping contrast, and Table 4 compares the available records. No radiographic long-dwell lack-of-fusion limit was identified within 0–240 s; this does not establish that no such limit exists.

Table 4

Dwell-wise evidence for the twelve released walls. Radiographic cells give the reported verdict and indication category (2 = porosity; 3 = clustered porosity); geometry cells reproduce the simplified macrograph description. Metallography cells state that the released reports provide no wall-level lack-of-fusion classification; no verdict was inferred from the section images. The ER70S-6 hardness row gives the condition-level cap-region means. ER110S-G hardness is unavailable

	Interlayer dwell time, t_d (s)					
	0	30	60	90	120	240
ER70S-6 radiography	rejected (2, 3)	accepted (none)	accepted (2)	accepted (2)	accepted (2)	rejected (2, 3)
ER70S-6 geometry	short / bulged	tall / straight	tall / straight	tall / straight	tall / straight	tall / straight; late-layer instability
ER70S-6 cap hardness (HV0.3)	177.8	176.0	175.4	179.3	180.8	187.1
ER70S-6 metallography	wall-level LoF classification not reported					
ER110S-G radiography	accepted (none)	accepted (none)	accepted (none)	accepted (2)	accepted (none)	accepted (2)
ER110S-G geometry	short / bulged	tall / straight	tall / straight	tall / straight	tall / straight	tall / straight
ER110S-G metallography	wall-level LoF classification not reported					

4.4 Hardness response and its within-wall variation

Hardness is the only dataset quantity with repeated within-wall measurements. The report provides one transverse section from each ER70S-6 wall, with two indentation tracks labelled 1 and 2, yielding 42–62 HV0.3 indentations per wall (Table 5). Its Inf and Sup labels are designated root and cap here only as shorthand; no fixed metric boundaries or coordinates are supplied. Because each condition contains one wall, the indentation data are nested rather than build replicates. Track means and individual spread are reported descriptively, without a population-level confidence interval. Root hardness is roughly 50 HV0.3 higher, and root indentations account for 14% at 30 s to 32% at 240 s. A pooled mean would confound dwell response with sampling composition; cap-region hardness is therefore the primary regional result.

Table 5

ER70S-6 Vickers hardness (HV0.3) by dwell condition. The root and cap labels reproduce the report's Inf and Sup groupings; they are not fixed-distance regions. Their means differ by roughly 50 HV0.3, and the fraction of root indentations varies from 14% to 32%, so a pooled wall mean is not comparable across conditions. Cap SD is the standard deviation of individual cap indentations; the last two columns give the means of the two indentation tracks on the same transverse section. The 30 s root mean excludes track 1, whose root row duplicates its cap row (Section 2.4). The fractional changes reported in Section 4.5 are calculated from the unrounded condition means. ER110S-G hardness is unavailable.

Dwell (s)	n root / cap	Root mean	Cap n	Cap mean	Cap SD	Cap track 1	Cap track 2
0	12 / 30	226.7	30	177.8	14.5	176.1	179.7
30	7 / 42	224.7	42	176.0	12.8	173.9	178.2
60	18 / 42	236.3	42	175.4	11.1	175.0	175.7
90	14 / 44	240.5	44	179.3	13.3	180.3	178.4
120	12 / 34	238.5	34	180.8	15.5	182.7	178.8
240	20 / 42	234.8	42	187.1	10.4	188.0	186.1

Cap-region hardness increased from 176.0 HV0.3 at 30 s to 187.1 HV0.3 at 240 s; the five observed condition-level means were nearly monotonic ($\rho = +0.90$). The 6.3 HV0.3 increase between 120 and 240 s is the largest cumulative interval difference, but that interval spans 120 s—four times the preceding intervals—so it does not establish the fastest rate of change. Excluding the 240 s wall reduced the rank correlation to $\rho = +0.80$; exact permutation values are in Supplementary Table S10. The 11.0 HV0.3 endpoint difference is of the same order as the expanded uncertainty reported for one indentation; without covariance information, no significance or build-to-build effect is assigned to it. The two cap-track means differed by 0.7–4.3 HV0.3 and describe within-section heterogeneity only. Root-region hardness showed no corresponding dwell ordering ($\rho = +0.30$).

Pooling root and cap indentations produced a sampling-composition artefact because the proportion of harder root measurements differed among conditions. The 0 s cap mean (177.8 HV0.3) differed from the 30 s mean by 1.7 HV0.3, of the same order as the within-section track differences, whereas pooled means (191.7 and 183.0 HV0.3) reversed that comparison.

The regional contrast is consistent with stronger baseplate conduction at the root and greater interpass sensitivity in the cap, in line with reports that lower interpass temperature and faster cooling favour a harder transformation product [14–17]. This mechanism is not established here because wall interpass temperature, cooling rate and phase content were not measured.

4.5 Cross-indicator comparison

Geometry changed mainly at shorter dwell, whereas radiographic classification and cap hardness did not define a matching dwell ordering. No clear plateau appears in the observed cap-region means. The non-

equidistant dwell grid and the single 240 s endpoint make the late hardness change a cumulative comparison, not a rate. Together, these observations show why the indicators should not be collapsed into one process boundary.

Over 30–240 s, average layer height completed 45.2% of its change by 60 s and 71.0% by 120 s (29.0% thereafter), whereas cap hardness reached 42.8% by 120 s and 57.2% thereafter (Fig. 4). These are cumulative fractions over unequal intervals, not rates; the hardness fraction after 120 s also depends on the single 240 s wall. Over 0–240 s, the geometric change was already 71.6% complete at 30 s in ER70S-6 and 73.8% in ER110S-G.

After correction of the even-sample calculation, the conventional medians of the minima between consecutive detected T3 peaks were 136.65, 109.85, 85.10 and 57.60°C for the 30, 60, 90 and 240 s workbooks, respectively. The corresponding interval counts were 4, 4, 9 and 7. Because the intervals were not registered to common deposited layers and several spanned missed thermal cycles, these values are retained only as an unregistered baseplate-channel diagnostic, not as validation of wall interpass temperature or layer-wise cooling.

5 Discussion

5.1 Where the indicators agree and where they diverge

The principal contribution of this work is not a new dwell-time recommendation but a decision-aware workflow for interpreting sparse manufacturing datasets. The indicators can diverge because slumping and cap-region hardness need not respond to the same part of the thermal cycle. Once cooling suppresses deformation, further cooling may alter transformation behaviour without materially changing wall shape. That mechanism is plausible but is not tested by the unregistered T3 diagnostic. The fitted scales for ER70S-6 (22.2 s) and ER110S-G (20.2 s) are descriptors on the nominal-dwell axis, not transferable thermal parameters; the alloys also differ in layer count and average-layer-height range.

Radiographic acceptance cannot replace the other indicators: a short-dwell wall may still slump, whereas the isolated ER70S-6 rejection at 240 s does not show that dwell above 120 s is generally unacceptable. Category 11 was not reported, but the metallographic reports provide no wall-level fusion verdict, and finite sectioning could not in any event establish whole-wall absence or an upper dwell limit (Section 4.3).

5.2 Engineering interpretation

Geometry alone cannot define a unique engineering boundary. A defensible screening workflow should first audit source provenance, assign a separate role to each indicator, and report fitted crossings separately from tested-grid bounds together with criterion, model, anchor and rounding sensitivity. The same sequence can be applied to sparse datasets from other manufacturing processes, including LPBF, DED, cold spray and laser cladding, provided that the indicators and acceptance criteria are defined for

that process. The present study demonstrates the workflow on WAAM data; it does not claim cross-process validation.

5.3 Within-wall hardness evidence

The two cap-track means assess within-section heterogeneity on one released cross-section, not section-to-section or build-to-build reproducibility (Section 4.4).

The dwell ordering in the condition-level cap means is endpoint-sensitive and absent at the root (Section 4.4). This contrast is compatible with, not evidence of, a thermal mechanism. A geometry-based dwell cannot establish a fixed cap-region hardness state.

5.4 Limitations

Four limitations set the scope. Each alloy–dwell condition has one wall, and no condition lies between 0 and 30 s, so build variability and response shape in that interval are unresolved. Hardness is confined to one unregistered section per ER70S-6 wall (two tracks), while ER110S-G hardness is absent; because wall height co-varies with dwell and the root–cap gradient is large, registration error could be systematic rather than random, but its magnitude and sign are unknown. Radiographic labels were transcribed, indication sizes are unavailable, detectability is finite [28, 29], and ER110S-G provenance is incomplete. The reduced calculation is neither mesh-converged nor calibrated, and the T3 diagnostic comprises unregistered intervals from four baseplate-channel workbooks and misses thermal cycles; neither provides wall interpass temperature.

6 Conclusions

- The geometric result depended on the recovery criterion, response law, zero-dwell anchor and height rounding. Across the tested choices, the tested-grid bound ranged from 30 to 240 s, with one crossing beyond the tested range.
- The quality indicators did not identify a common dwell boundary. Geometry changed mainly at shorter dwell. The ER70S-6 condition-level cap means showed no clear plateau, but the 120–240 s cumulative difference spans a fourfold longer interval and one endpoint wall, so it does not establish a late-stage rate. Radiographic classification showed no resolvable monotonic ordering with dwell. Geometric stabilisation therefore does not by itself establish a fixed cap-region hardness state.
- The transferable contribution is a traceable sensitivity workflow for sparse manufacturing data: source records are linked to extracted values, analytical choices are varied explicitly, and geometry, radiography and hardness remain separate evidence streams. Applied to one wall per condition, the workflow identifies what the dataset can screen but cannot establish without repeated builds and qualified acceptance criteria.

Declarations

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No funding was received for conducting this study.

Author Contribution

J.J. conceptualised the study, developed the methodology, performed the software implementation, validation, investigation, formal analysis and data curation, prepared the visualisations, and wrote the original manuscript draft. J.L. contributed supervision and reviewed and edited the manuscript. A.Z. contributed supervision and project coordination. V.K. contributed supervision. All authors reviewed and approved the final manuscript.

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Data Availability

All data analysed in this study are available in the Zenodo repository:
<https://doi.org/10.5281/zenodo.17608626> (CC BY 4.0). The supplementary files and reproducibility package provide the extracted records, source mapping, sensitivity analyses and scripts used in this study.

Code availability

The submitted reproducibility package contains the extracted evidence table, model inputs and scripts required to regenerate Tables 1–5, Supplementary Table S3 and Figs. 1–4. It is available to reviewers with Supplementary Tables S1–S13 and will be deposited under a persistent identifier after acceptance.

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Figures

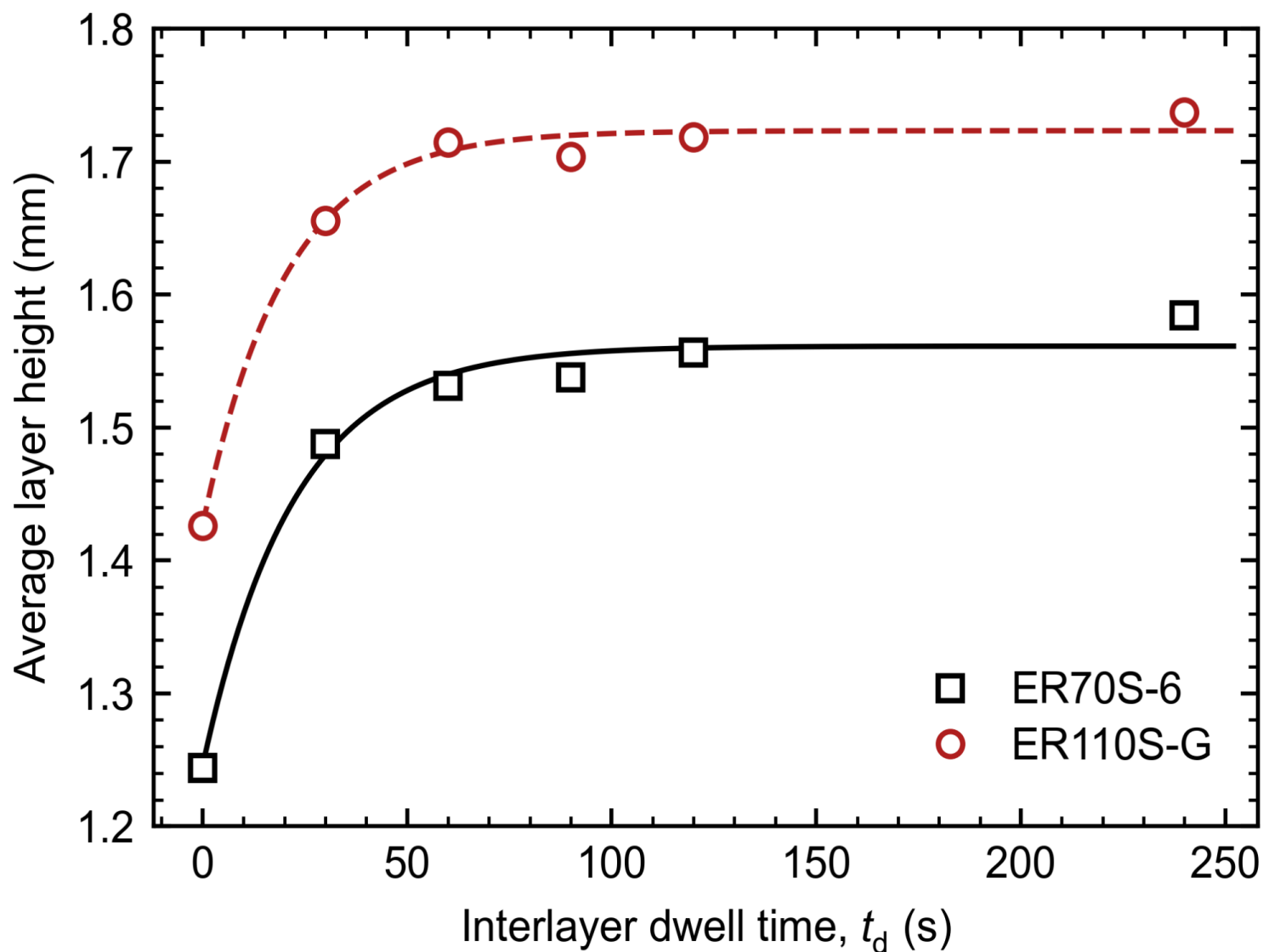


Figure 1

Average layer height against interlayer dwell time, with full-data exponential fits. Symbols are the released observations. No error bars are shown because the dataset provides one wall per condition; the leave-one-out refits are given in Supplementary Table S11

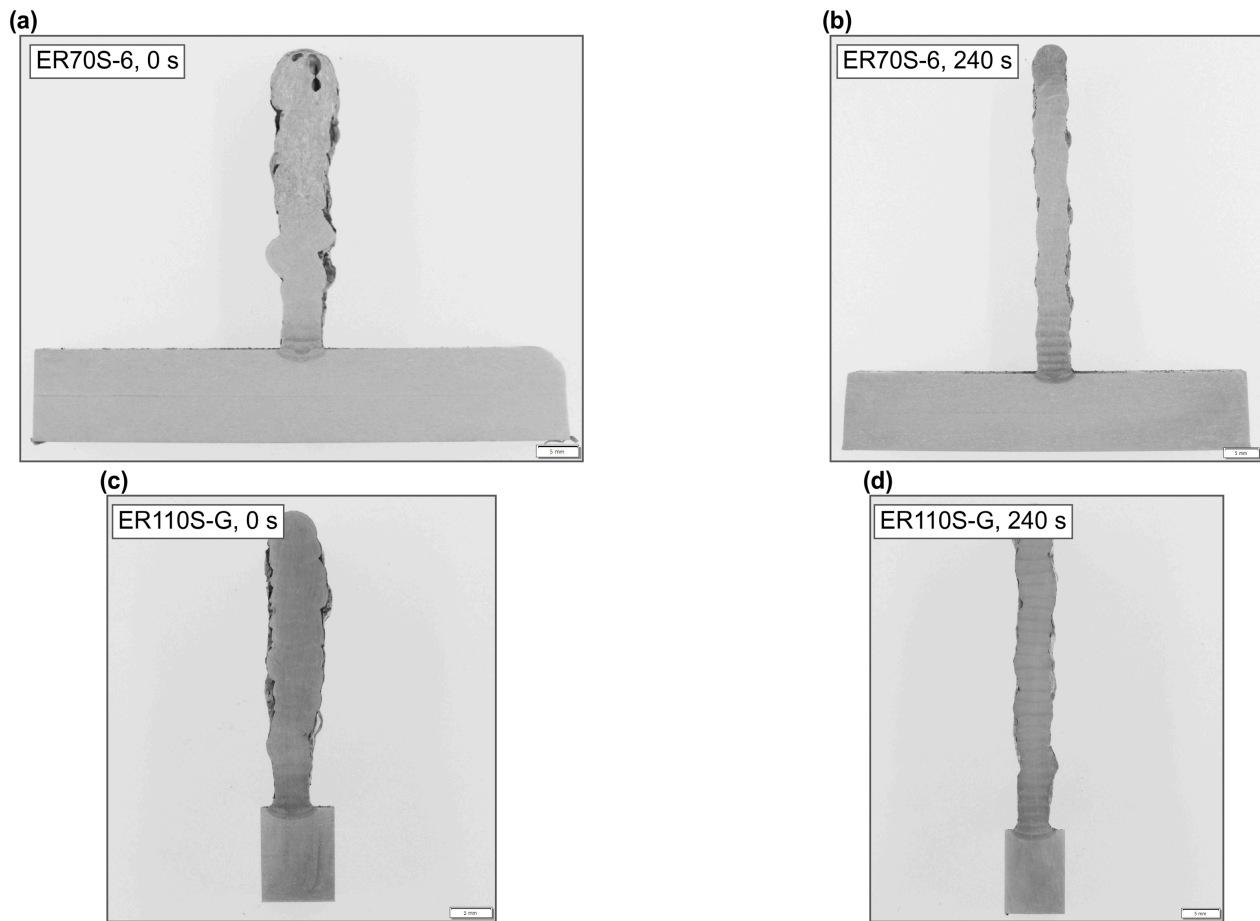


Figure 2

Representative endpoint macrographs adapted from the AIMEN/PIONEER destructive-testing dataset [21] under CC BY 4.0, with the released scale bars retained: ER70S-6 and ER110S-G at 0 and 240 s. The 0 s cases show slumping and bulging. The images illustrate macro shape; they are not used here to assign a wall-level lack-of-fusion verdict

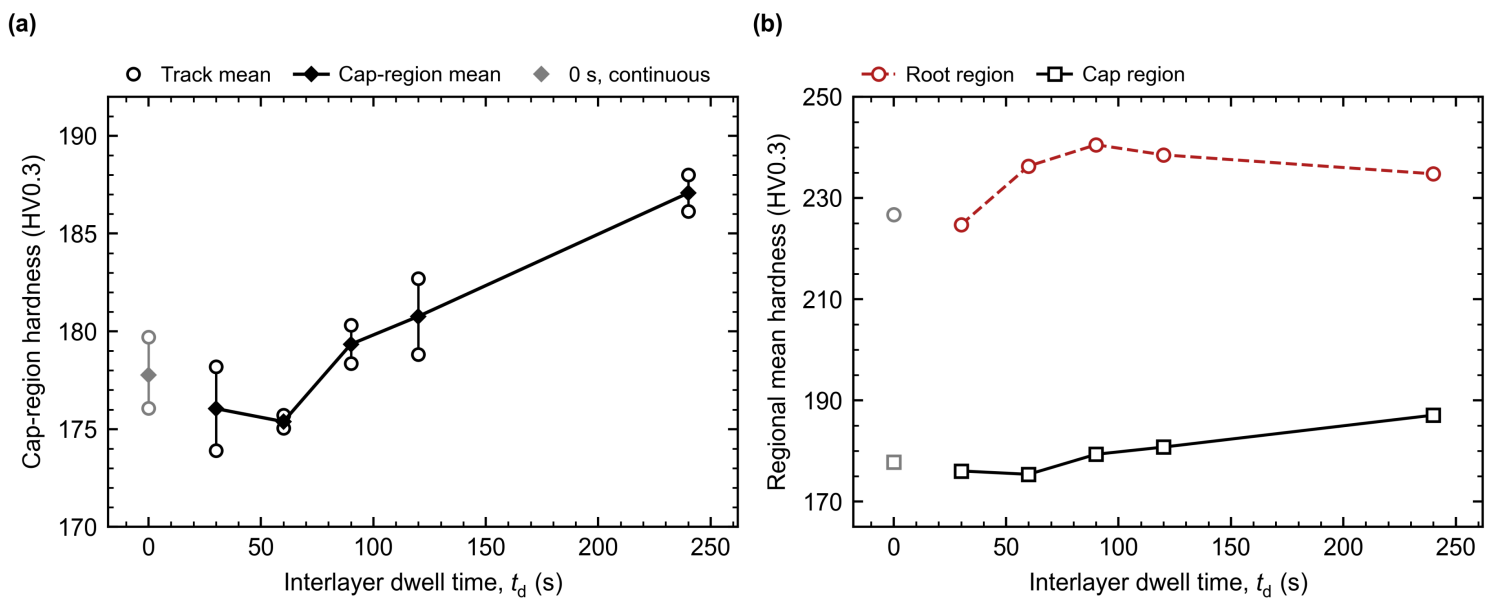


Figure 3

ER70S-6 Vickers hardness against interlayer dwell time. (a) Cap region: open circles are the two indentation-track means from the single released cross-section of a wall, the line joins them, and the filled diamond is the pooled mean of all cap-region indentations. The pooled mean is used consistently in Table 5 and panel (b). No confidence interval is drawn because one wall represents each condition; individual values are in Supplementary Table S8. (b) Root and cap means of the same walls. The continuous-deposition condition is grey throughout

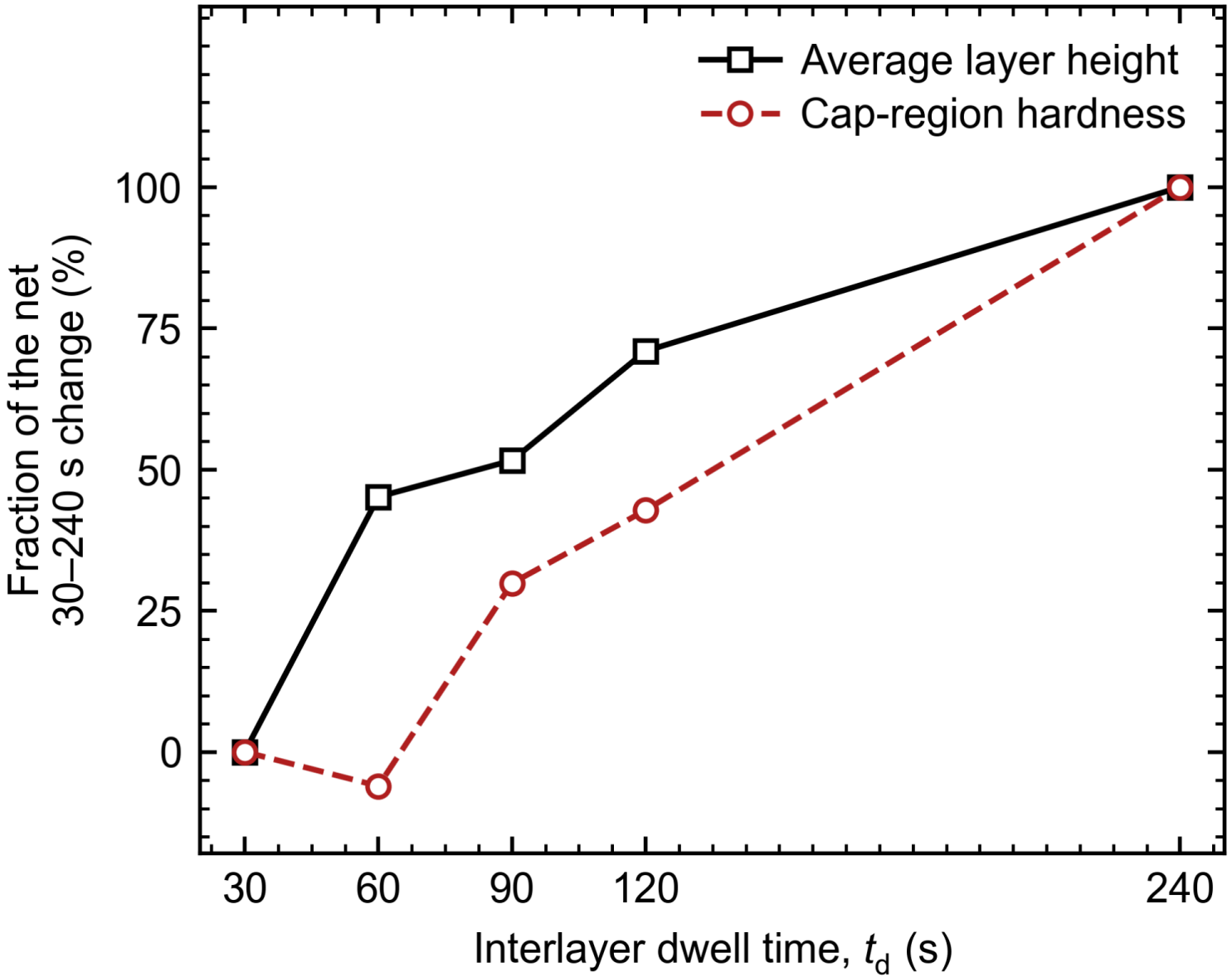


Figure 4

Average layer height and ER70S-6 cap-region hardness, each referred to its own change over the 30–240 s interval; the vertical axis is a completed fraction, not a physical quantity. Fractions use unrounded condition means. The 120–240 s interval is four times wider than the preceding intervals, so the late

hardness fraction is cumulative change rather than a rate and depends on the single 240 s wall. The 60 s hardness value lies slightly below the 30 s value, within the track-to-track spread of Fig. 3a

Supplementary Files

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