

CEN/CEN WS XXX

Date: 2026-10

Draft CWA XXXXX: XXXX

Workshop: XXX

**Integration of additive manufacturing into conventional production for
aluminium body-in-white components — Guidelines for manufacturing
and structural performance validation**

CCMC will prepare and attach the official title page.

Contents	Page
Foreword.....	4
Introduction	6
1 Scope.....	7
2 Normative references.....	7
3 Terms and definitions	8
3.1 Symbols	8
3.2 Abbreviations.....	9
4 General principles and workflow	10
5 Design of hybrid aluminium components and reinforcements	10
5.1 Functional definition	10
5.2 Selection of reinforcement zones.....	10
5.3 Loading state of the reinforcement.....	11
5.4 Layout screening.....	11
5.5 Manufacturability constraints	12
6 Materials and feedstock	12
6.1 Substrate	12
6.2 Powder.....	12
6.3 Feedstock selection considerations	12
6.4 Feedstock characterisation methodology.....	13
7 DED-LB/P equipment and process environment.....	13
7.1 Equipment description	13
7.2 Atmosphere and shielding.....	13
7.3 Fixturing and thermal boundary conditions	14
7.4 Equipment verification methodology.....	14
7.5 Fixturing qualification	15
8 Process development and manufacturing qualification.....	15
8.1 General.....	15
8.2 Single-track design of experiments.....	16
8.3 Qualification outputs.....	16
8.4 Detailed single-track methodology	16
8.5 Confirmation of the process window.....	18
9 Manufacturing of reinforcement structures	18
9.1 Surface preparation	18
9.2 Thin-wall strategy.....	18
10 Post-processing, inspection and quality assurance	20
10.1 Inspection planning and sampling	20
10.2 Visual, dimensional and quality inspection	21
10.3 Mechanical characterisation at specimen scale: three-point bending.....	22
10.4 Mechanical characterisation at specimen scale: fracture assessment.....	25
10.5 Mechanical characterisation at specimen scale: fatigue assessment	29
10.6 Mechanical characterisation at component level: crash assessment.....	33

11	Reporting, traceability and decision criteria	37
12	Limitations, transferability and safety	38
	Bibliography	39

Foreword

This CEN Workshop Agreement (CWA XXXX:YYYY) has been developed in accordance with the CEN-CENELEC Guide 29 “CEN/CENELEC Workshop Agreements — A rapid way to standardization” and with the relevant provisions of CEN/CENELEC Internal Regulations - Part 2. It was approved by the Workshop CEN “Integration of additive manufacturing into conventional production for aluminium body-in-white components”, the secretariat of which is held by “UNE- Spanish association for standardization” consisting of representatives of interested parties on YYYY-MM-DD, the constitution of which was supported by CEN following the public call for participation made on 2026-08-20. However, this CEN Workshop Agreement does not necessarily include all relevant stakeholders.

The final text of this CEN Workshop Agreement was provided to CEN for publication on YYYY-MM-DD.

Results incorporated in this CWA received funding from the Horizon Europe programme under grant agreement No. 101069674.

The following organizations and individuals developed and approved this CEN Workshop Agreement:

- Hannah Arpke (FUNDACIO EURECAT), Chair
- Sergi Parareda (FUNDACIO EURECAT)
- Natalia Carmona (FUNDACIO EURECAT)
- Míriam Vendrell (FUNDACIO EURECAT)
- Alessio Tommasi (GEMMATE TECHNOLOGIES S.R.L.)
- Maddalena Rugolo (GEMMATE TECHNOLOGIES S.R.L.)
- Martina BRUNO (GEMMATE TECHNOLOGIES S.R.L.)
- Andrea Bertinetti (GEMMATE TECHNOLOGIES S.R.L.)
- Francesco Bruzzo (FRAUNHOFER INSTITUTE FOR MATERIAL AND BEAM TECHNOLOGY IWS)
- Stefan Heins (FRAUNHOFER INSTITUTE FOR MATERIAL AND BEAM TECHNOLOGY IWS)
- Andoni Agirre
- Diego Argote
- Javier López (UNE), Secretary

Attention is drawn to the possibility that some elements of this document may be subject to patent rights. CEN-CENELEC policy on patent rights is described in CEN-CENELEC Guide 8 “Guidelines for Implementation of the Common IPR Policy on Patent”. CEN shall not be held responsible for identifying any or all such patent rights.

Although the Workshop parties have made every effort to ensure the reliability and accuracy of technical and non-technical descriptions, the Workshop is not able to guarantee, explicitly or implicitly, the correctness of this document. Anyone who applies this CEN Workshop Agreement shall be aware that neither the Workshop, nor CEN, can be held liable for damages or losses of any kind whatsoever. The use of this CEN Workshop Agreement does not relieve users of their responsibility for their own actions, and they apply this document at their own risk. The CEN Workshop Agreement should not be construed as legal advice authoritatively endorsed by CEN/CENELEC.

Introduction

Hybrid manufacturing enables additive manufacturing processes to be integrated into conventional production routes by depositing local features on preformed components. In aluminium body-in-white applications, Directed Energy Deposition using a laser beam and powder feedstock (DED-LB/P) can be used to manufacture local reinforcement structures on extruded, sheet-based or cast substrates. These features can be designed to modify local stiffness, folding behaviour, peak force, energy absorption or another component-level response while limiting the amount of additional material.

The structural performance of a hybrid component depends not only on the geometry and position of the deposited reinforcement but also on the interaction between the substrate, deposited material, reinforcement root and interface. The local thermal cycle generated during deposition can produce dilution, a heat-affected zone, residual stresses, distortion, porosity and lack of fusion. In addition, the reinforcement can experience tension, compression, bending or interface shear as the component deforms. Consequently, reinforcement design, material selection, process development, manufacturing, inspection and mechanical validation should be treated as an integrated qualification workflow.

This document provides guidance for developing and validating DED-LB/P reinforcements for thin aluminium components. The manufacturing methodology progresses from substrate and feedstock characterisation through equipment verification, single-track parameter development and qualification of representative multilayer geometries. Particular attention is given to thin walls, intersections, curved paths, track starts and terminations, fixturing, thermal accumulation and process-induced distortion.

Inspection and quality assurance are used to assess reinforcement geometry, position, penetration or dilution, interface continuity, porosity, lack of fusion, cracking, heat-affected regions and component distortion. The selected inspection methods and acceptance criteria should reflect the expected defect types, component geometry, structural function and demonstrated detection capability.

Mechanical characterisation is performed at specimen and component levels. Three-point bending may be used to compare reinforced and unreinforced specimens and to evaluate the effect of loading the reinforcement in tension or compression. Fracture assessment can combine the Essential Work of Fracture method for thin ductile substrates with comparative notched-bending tests for deposited features that cannot be represented by standard pre-cracked specimens. A stepwise stiffness method may be applied for rapid comparative fatigue screening, while conventional constant-amplitude fatigue testing remains necessary where S-N curves, survival probabilities or design allowables are required. Component-level high-speed testing is used to assess progressive folding, force-displacement response, absorbed energy, cracking and interface separation under representative dynamic loading.

Numerical models may support reinforcement-layout screening, process development and interpretation of structural tests. Such models should be calibrated and validated against appropriate experimental evidence, including deposited geometry, distortion, force, energy, deformation sequence and failure location. Model applicability shall remain limited to the materials, geometries, process conditions and loading cases for which adequate validation has been demonstrated.

The procedures in this document are intended to support reproducible development and comparative validation. They do not prescribe universal deposition parameters, defect limits, material allowables, certification rules or vehicle homologation requirements. Numerical values and configurations presented as examples shall be adapted and validated for the applicable material, machine, fixture, reinforcement geometry, component and loading condition. Environmental and economic assessment of hybrid manufacturing routes is outside the scope of this document and is addressed separately.

1 Scope

This document provides guidelines for the design, manufacture, inspection and structural validation of hybrid aluminium body-in-white components incorporating local reinforcement features produced by Directed Energy Deposition using a laser beam and powder feedstock (DED-LB/P). It is applicable primarily to thin-walled aluminium components manufactured by conventional processes, including extrusion, sheet forming and casting, and subsequently reinforced by DED-LB/P. The procedures may also be applied to representative coupons and demonstrator components used to qualify the manufacturing route and validate structural performance.

This document covers:

- definition of the reinforcement function, loading condition and measurable performance indicators;
- selection and characterisation of the substrate and powder feedstock;
- verification of DED-LB/P equipment, atmosphere, fixturing and relevant process conditions;
- development and qualification of process parameters using single tracks and representative multilayer geometries;
- manufacture of thin walls, intersections, curved tracks and other local reinforcement features;
- visual, dimensional, metallographic and non-destructive inspection;
- assessment of reinforcement geometry, penetration or dilution, interface continuity, defects, heat-affected regions and component distortion;
- specimen-scale characterisation by three-point bending, fracture assessment and fatigue testing;
- component-level validation under quasi-static or high-speed loading;
- calibration and validation of mechanical numerical models;
- reporting, traceability, nonconformance management and conditions requiring requalification.

The document does not prescribe universal process parameters, material properties, defect-acceptance limits, design allowables or production-control limits. Values and configurations presented as examples shall be confirmed for the applicable material, machine, substrate thickness, fixture, reinforcement geometry and loading condition.

This document does not establish certification schemes, vehicle homologation requirements or regulatory crash-test procedures. Environmental and economic assessment of hybrid manufacturing routes is outside its scope.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

CWA 17793:2021, *Test method for determination of the essential work of fracture of thin ductile metallic sheets*

CWA 18107-2:2024, *Advanced fatigue testing methods — Part 2: Stiffness method*

ASTM E1820, *Standard Test Method for Measurement of Fracture Toughness*

ASTM E399, *Standard Test Method for Linear-Elastic Plane-Strain Fracture Toughness K_{IC} of Metallic Materials*

ISO 1099, *Metallic materials — Fatigue testing — Axial force-controlled method*

3 Terms and definitions

For the purposes of this document, the following symbols and abbreviations apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- ISO Online browsing platform: available at <http://www.iso.org/obp/>
- IEC Electropedia: available at <http://www.electropedia.org/>

3.1 Symbols

b	specimen width
$E(\delta_i)$	energy absorbed up to displacement δ_i
F	applied or measured force
$F(\delta)$	force as a function of displacement
$F(u)$	force as a function of specimen displacement
$F_{\min}$	minimum force in a fatigue cycle
$F_{\max}$	maximum force in a fatigue cycle
F_f	characteristic force determined from the change in slope of the diagnostic fatigue response
F_{mean}	mean crush force over a defined displacement interval
J_{IC}	critical value of the J -integral satisfying the applicable validity requirements
J_Q	provisional or conditional J -integral value
K_{IC}	plane-strain fracture toughness satisfying the applicable validity requirements
K_Q	provisional or conditional stress-intensity factor
L	support span in a three-point bending test
l_0	initial uncracked ligament length
m	mass used to calculate mass-specific energy absorption
N	number of fatigue cycles
P	applied cyclic load, as represented in the stepwise fatigue-loading diagram
P_c	constant diagnostic load used between fatigue blocks
R	stress ratio, $\sigma_{\min}/\sigma_{\max}$
R_F	force ratio, $F_{\min}/F_{\max}$
t	specimen or substrate thickness
u	measured specimen displacement

u_f	specimen displacement at complete fracture
W_f	total work of fracture
w_e	specific essential work of fracture
w_f	specific total work of fracture
w_p	specific non-essential plastic work
β	geometric factor associated with the shape of the plastic zone
δ	measured displacement or component crush displacement
δ_i	specified displacement up to which absorbed energy is calculated
δ_1, δ_2	lower and upper limits of the displacement interval used to calculate mean crush force
$\sigma_{\min}$	minimum nominal stress in a fatigue cycle
$\sigma_{\max}$	maximum nominal outer-fibre bending stress or maximum nominal stress in a fatigue cycle

3.2 Abbreviations

3D	three-dimensional
ASTM	ASTM International
CAD	computer-aided design
CCMC	CEN-CENELEC Management Centre
CEN	European Committee for Standardization
CENELEC	European Committee for Electrotechnical Standardization
CWA	CEN Workshop Agreement
DED-LB/P	directed energy deposition using a laser beam and powder feedstock
DENT	double-edge-notched tensile
DIC	digital image correlation
DoE	design of experiments
ED	extrusion direction
EDM	electrical discharge machining
EWf	essential work of fracture
HAZ	heat-affected zone
IEC	International Electrotechnical Commission
ISO	International Organization for Standardization
NDT	non-destructive testing
PSD	particle-size distribution
S-N	stress-life fatigue relationship

4 General principles and workflow

The qualification workflow shall link the structural function of the reinforcement to manufacturing feasibility and experimental validation. The recommended sequence is:

- define component function, load case, deformation mode and measurable performance indicators;
- identify reinforcement zones and intended trigger zones;
- screen candidate layouts by analysis or simulation;
- characterise substrate and feedstock;
- develop the deposition process using single tracks;
- qualify representative walls, intersections and curved tracks;
- manufacture representative coupons and components;
- inspect geometry, defects, HAZ and distortion;
- characterise the substrate, deposited feature and interface under relevant loading states;
- validate the component at the relevant loading rate;
- compare test and model predictions, document limitations and freeze the qualified route.

NOTE 2 A change in machine, optical system, powder batch or PSD, substrate alloy or temper, substrate thickness, clamping, shielding arrangement, deposition geometry, heat treatment or critical process parameter shall trigger a documented review of the qualification evidence.

5 Design of hybrid aluminium components and reinforcements

5.1 Functional definition

The design input shall specify whether the reinforcement is intended to increase local stiffness, change the location or sequence of folding, reduce peak force, increase absorbed energy, delay local buckling, protect a weak region or provide another function [1]. The target shall be expressed using measurable indicators such as force-displacement response, absorbed energy over a defined displacement, peak force, number and location of folds, mass addition, crack occurrence and interface delamination.

5.2 Selection of reinforcement zones

Reinforcements should be placed with reference to the expected deformation field. In axial crushing, unreinforced regions can be retained as controlled folding triggers. The number and spacing of gaps shall be treated as design variables. Continuous deposition is not intrinsically beneficial because added material can alter the folding mechanism, peak force, and energy-absorption response.

5.3 Loading state of the reinforcement

The design shall distinguish regions in which the reinforcement is expected to be loaded in tension, compression, bending or mixed-mode interface loading. Coupon tests showed that a straight reinforcement on the tensile side of a bending specimen cracked early and produced only a small increase in absorbed energy, whereas the same reinforcement on the compression side produced a substantially higher force and energy absorption. Reinforcement orientation should therefore favour compression where compatible with the required component deformation.

5.4 Layout screening

Layout screening shall be performed before detailed process qualification. The objective is to eliminate concepts that are incompatible with the intended deformation mode, add disproportionate mass, create inaccessible deposition paths or introduce critical intersections and tensile-loaded roots. Screening shall compare each candidate with an unreinforced reference using the same component geometry, boundary conditions, and performance indicators (Table 1).

Figure 1 illustrates four topology families that may be considered during initial screening. The drawings are schematic. Track spacing, feature dimensions, and the number of gaps or intersections shall be established for the specific component.

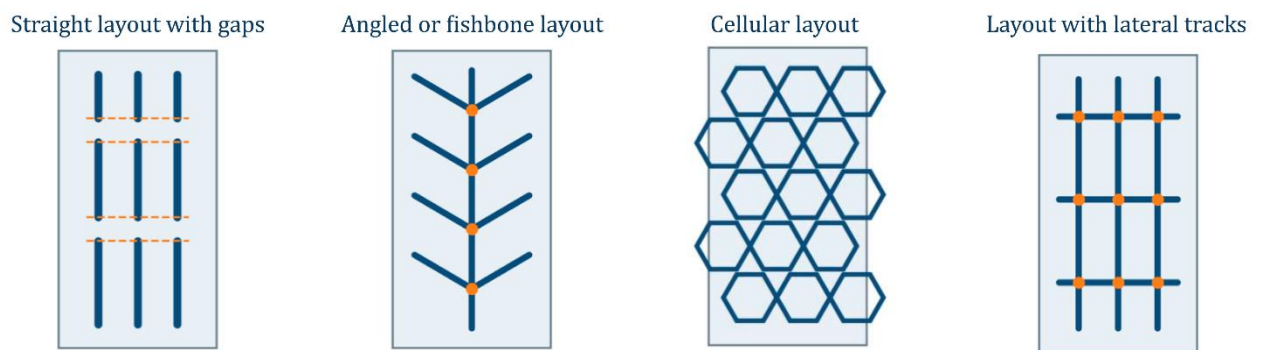


Figure 1 — Schematic reinforcement-layout families for preliminary screening. Blue: deposited reinforcement. Orange: gaps or intersections requiring specific assessment.

Table 1 — Assessment considerations and main design implications for each layout family

Layout family	Assessment considerations	Design implications
Straight layout with gaps	Gap number and spacing; continuity of longitudinal load transfer; deposited mass; trigger locations.	Provides a simple reference configuration. Verify that unreinforced regions initiate the intended folding sequence and that reinforced segments do not cause an excessive peak force.
Angled or fishbone layout	Local tensile strain in inclined tracks; intersection geometry; path acceleration; overlap and heat concentration.	Can redistribute load and influence fold development. Intersections and inclined roots shall be qualified because they can become local failure locations.
Cellular layout	Deposited mass; track density; repeated intersections; heat accumulation; accessibility and inspection coverage.	Can provide multi-directional support but can be inefficient in mass and difficult to manufacture. Use only when the structural benefit justifies process complexity.

Layout family	Assessment considerations	Design implications
Layout with lateral tracks	Loading state of transverse tracks; intersection bonding; constraint of local folding; interface shear.	Can increase local constraint and connect longitudinal ribs. Validate feature and interface failure under representative deformation and loading rate.

Candidates should be ranked using a documented multi-criteria assessment. No single indicator, including predicted absorbed energy, shall be used as the sole selection criterion.

5.5 Manufacturability constraints

The reinforcement geometry shall be compatible with deposition-head access, stand-off control, powder-stream focus, stable clamping and thermal dissipation. The substrate shall not be perforated or excessively distorted. For thin substrates, cross-section, height, track sequence, and pause strategy shall be selected together rather than independently.

6 Materials and feedstock

6.1 Substrate

The substrate record shall include alloy designation, temper, manufacturing route, nominal and measured thickness, orientation, surface condition, prior heat treatment, and relevant mechanical properties. Process-development coupons and component-validation specimens shall reproduce the applicable thickness, material condition, and thermal boundary conditions to the extent required by the qualification plan.

6.2 Powder

The powder specification shall include alloy designation, supplier or production route, batch identifier, particle-size distribution, chemical composition, morphology and storage history. Powder handling shall prevent moisture uptake and cross-contamination. The suitability of recycled or internally atomised feedstock shall be demonstrated by the same quality and traceability principles as commercial powder.

6.3 Feedstock selection considerations

The feedstock alloy and particle-size distribution shall be selected for the deposition system and target feature (Table 2). For internally atomised or composition-modified powder, billet preparation, melt temperature and atomisation conditions can affect element recovery, particle morphology and fraction yield. Chemical composition shall therefore be measured on the produced powder and shall not be inferred solely from the charge composition.

Table 2 — Powder acceptance record

Characteristic	Minimum record
Identity	Alloy, batch, supplier or atomisation run
Particle-size distribution	Method, sieve or measured fractions, date
Morphology	Representative microscopy and qualitative/quantitative assessment
Chemical composition	Method, elements measured, uncertainty where available
Condition	Drying, storage, reuse history and contamination controls
Flow/feed behaviour	Powder feeder settings and observed stability

The feedstock alloy and particle-size distribution shall be selected for the deposition system and target feature. For

6.4 Feedstock characterisation methodology

Each powder batch used for qualification or production shall be sampled using a documented plan that minimises segregation by particle size. The sampling location, sample mass and subdivision method shall be recorded. Characterisation should be completed before first use and repeated after any reuse or blending operation that can modify the particle population.

- Determine particle-size distribution over a range that includes the nominal cut limits. Report the method, sample preparation, number of measurements, and the characteristic percentiles used by the laboratory.
- Assess particle morphology using representative microscopy. In addition to qualitative images, the report should identify irregular particles, satellites, agglomerates, and foreign particles where these are observed.
- Verify chemical composition using a method suitable for the alloy and the elements of interest. For internally atomised or modified alloys, do not infer composition from the charge because element recovery may differ during melting and atomisation.
- Record apparent density, flow, or powder-feeder stability when these variables affect dosing repeatability. The selected method and conditioning history shall be stated.
- Control moisture exposure through storage records, opening date, drying conditions and maximum permitted out-of-container time.

Powder acceptance shall be based on its demonstrated ability to produce stable feeding and deposits meeting the defined geometric and metallographic criteria. A particle-size interval alone is not sufficient evidence of suitability.

7 DED-LB/P equipment and process environment

7.1 Equipment description

The equipment description shall identify the machine, laser source and wavelength, nominal maximum power, optical spot, powder nozzle, powder feeder, carrier and shielding gases, motion system, working-envelope atmosphere and monitoring systems. Calibration or verification status of power, powder feed and motion shall be recorded.

7.2 Atmosphere and shielding

Aluminium processing requires control of oxidation and moisture. The atmosphere or local shielding arrangement shall be specified and verified for the selected material, geometry and deposition duration. Gas type, flow rate, purge sequence and relevant oxygen or moisture measurements shall be recorded. Values validated for one enclosure or shielding arrangement shall not be transferred without confirmation (Table 3).

Table 3 — Representative fixed settings for one validated experimental configuration — They are not universal requirements

Parameter	Informative example
Laser wavelength	1070 nm
Laser spot	0.8 mm
Powder spot	0.8 mm
Powder PSD	45-105 μm
Carrier gas	3 L/min Ar
Shielding gas	3 L/min Ar
Forming gas	6 L/min Ar

7.3 Fixturing and thermal boundary conditions

The fixture shall maintain part location while permitting predictable thermal contraction. Contact with the supporting table, clamped length, clamp force, and free edges shall be documented because they influence heat extraction and final distortion. The same boundary conditions should be reproduced during qualification and production. Where this is not possible, the effect of the change shall be evaluated experimentally or by a validated thermal-mechanical model.

7.4 Equipment verification methodology

Before process qualification, the user shall verify that the commanded process settings correspond to the delivered process conditions (Table 4). The verification interval shall be defined according to equipment stability, maintenance history, and the importance of the deposited feature.

Table 4 — Verification items

Item	Verification activity	Minimum record
Laser power	Measure output power at one or more levels spanning the intended window.	Commanded and measured power, device, date and uncertainty or tolerance.
Powder feed	Collect powder for a defined time at representative feeder settings.	Mass, duration, calculated feed rate and repeatability.
Motion	Verify path dimensions and travel speed using the machine controller or an independent measurement.	Program version, measured deviation and acceptance decision.
Coaxial alignment	Check coincidence of the laser spot, powder focus and programmed tool centre point.	Method, offsets and corrective action.
Atmosphere	Verify oxygen and moisture measurement before and during deposition.	Initial value, stable value, alarms and purge duration.
Stand-off	Verify nozzle-to-substrate distance and its variation along the path.	Nominal value, measured range and datum.

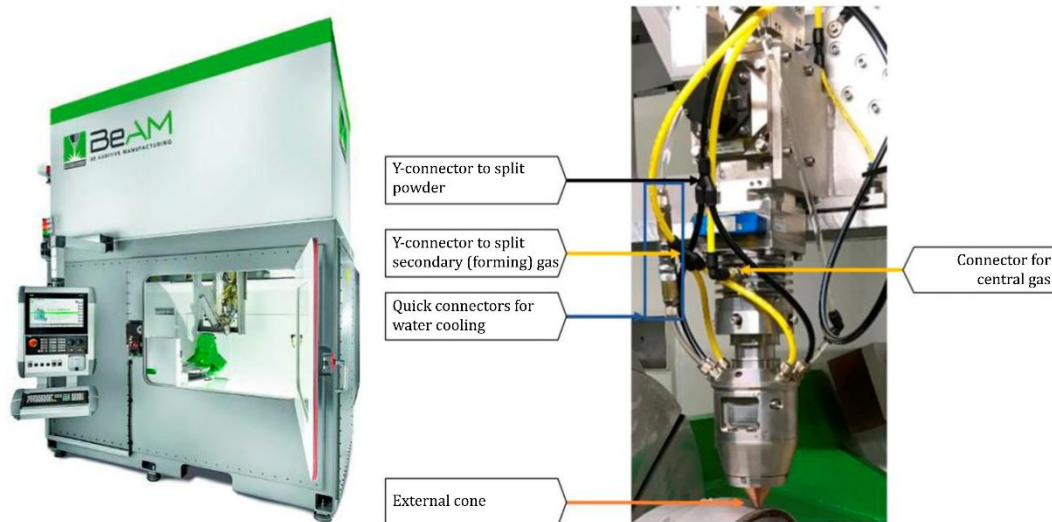


Figure 2 — Used industrial DED-LB/P equipment — Left: Machine with inert atmosphere capabilities — Right: Deposition head with laser-powder nozzle

7.5 Fixturing qualification

The fixture shall be treated as part of the qualified process. Qualification shall document the contact surfaces, clamping sequence, torque or force where controlled, unsupported length, thermal contact with the backing structure and time of unclamping. A dimensional survey before deposition and after complete cooling should be used to separate initial geometric deviation from process-induced distortion.

Where the component has variable curvature or thickness, stand-off and heat extraction shall be evaluated at the locations expected to produce the highest and lowest thermal accumulation. A flat coupon is not sufficient to qualify a fixture for a curved component unless equivalence has been demonstrated.

8 Process development and manufacturing qualification

8.1 General

Process development should proceed from simple to representative geometry (Table 5). A suitable sequence is single tracks, overlapping tracks or lower layers, thin walls, intersections or curves, representative coupons and finally the component. Each stage shall confirm both material quality and geometric accuracy.

Table 5 — Reinforcement process development

Stage	Specimen	Primary decision
Screening	Single tracks	Exclude unstable, poorly bonded or excessively penetrating conditions.
Optimisation	Structured DoE	Quantify effects and identify candidate settings.
Confirmation	Independent tracks	Verify geometry, bonding and repeatability.
Representative qualification	Wall, curve or intersection	Verify multilayer geometry and local defect risk.
Component confirmation	Full or representative component	Verify path access, distortion and final function.

8.2 Single-track design of experiments

The primary variables shall include laser power, travel speed and powder feed rate. Other variables, including stand-off distance, gas flow, track direction, substrate temperature and inter-pass time, shall be held constant or incorporated into the experimental design (Table 6). Track width, height, penetration or dilution, cross-sectional area, aspect ratio and visible defects shall be measured.

A statistically structured design, such as a central composite design, may be used where interaction and curvature effects are expected. The fitted response shall be checked through residual analysis and confirmation runs; statistical significance alone shall not replace metallographic examination or physical plausibility.

Table 6 — Informative process development example

Iteration	Laser power	Travel speed	Powder feed rate	Outcome
Initial range	700-900 W	1300-1700 mm/min	1.7-2.3 g/min	No track simultaneously met all geometry and material-quality targets.
Refined range	500-700 W	1000-1500 mm/min	1.3-1.7 g/min	Power significantly influenced width and dilution; speed and powder feed influenced height.
Selected point	600 W	1250 mm/min	1.5 g/min	Selected for the reported machine/material configuration, with an aspect ratio close to 1/4.

The selected point shall be treated as a centre point for confirmation, not as evidence that neighbouring combinations are acceptable. Repeatability shall be demonstrated with independent tracks and representative cross-sections.

8.3 Qualification outputs

- Documented parameter window and fixed settings;
- measured track geometry and dilution;
- metallographic evidence of bonding and defect condition;
- repeatability across positions or specimens;
- defined response to deviations such as lateral spray, widening or substrate curvature;
- representative-geometry confirmation.

8.4 Detailed single-track methodology

Single-track development shall establish the relation between controllable process inputs and track geometry, bonding and defects (Figure 3). The substrate material, temper, thickness, surface preparation, and thermal boundary condition shall be representative of the intended application [2]. If a thicker development plate is used, the results shall not be transferred to the component without confirmation of representative thickness.

- Define the target responses before testing. These normally include width, height, cross-sectional area, penetration or dilution, interface continuity, porosity, lack of fusion, surface continuity and substrate distortion.

- Select the factors and limits using preliminary trials that avoid cutting through the substrate, gross balling and unstable powder capture. Laser power, travel speed and powder feed rate are primary factors; stand-off, gas flow, substrate temperature and path direction shall either be fixed or included.
- Randomise the run order where practically possible and include repeated centre points to estimate repeatability and process drift. Record the location and direction of every track on the substrate.
- Section tracks at a defined steady-state position away from starts and stops. If transient behaviour is relevant, add sections at the start and termination.
- Fit response models only within the investigated factor space. Check residuals, lack of fit and confirmation runs. A statistically significant factor shall not be interpreted as a physically acceptable process if metallography shows defects.

For a track geometry analysis, the polished cross-section shall be oriented normal to the local deposition direction (Figure 3). Width and height shall be measured relative to the original substrate surface. Penetration shall be measured from that surface to the deepest fused point. Where the original surface cannot be reconstructed unambiguously, the measurement rule and associated uncertainty shall be documented.

At least one calibrated scale shall be included in the image record. Image segmentation shall distinguish deposited material, remelted substrate and preparation artefacts. When dilution is reported as a ratio, the geometric definition used shall be included because different communities use different area- or depth-based definitions.

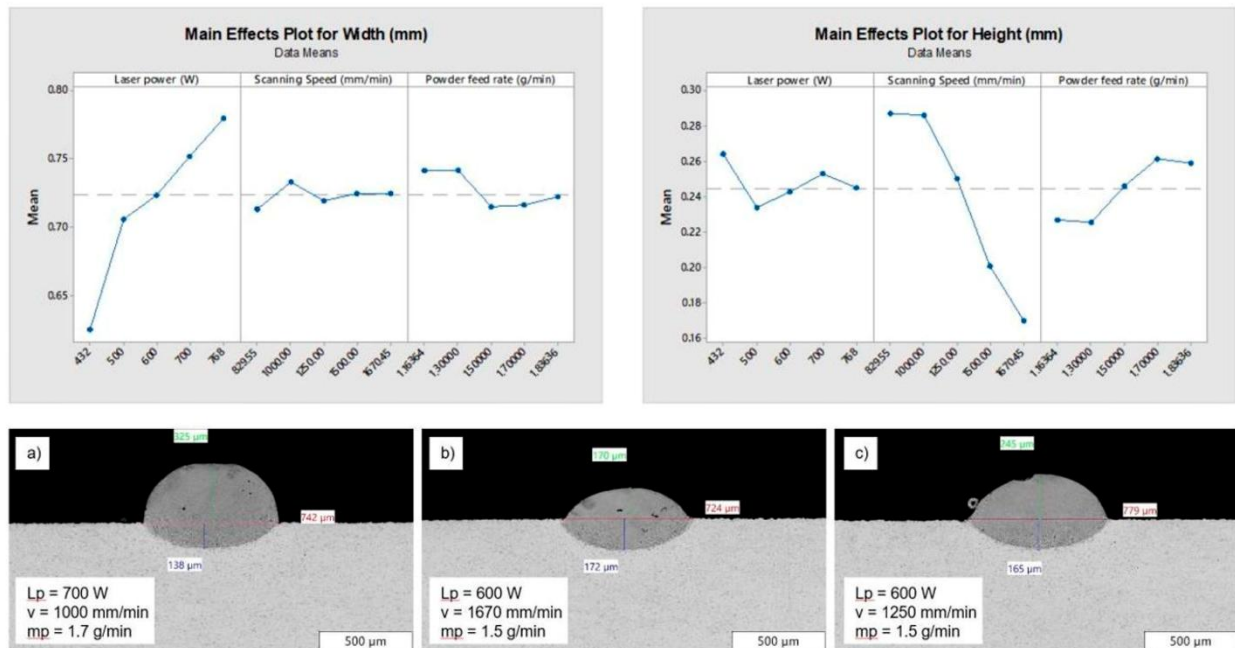


Figure 3 — Response plots and representative metallographic cross-sections used during DED-LB/P single-track parameter development

8.5 Confirmation of the process window

A selected parameter combination shall be confirmed using independent tracks produced after machine reinitialisation or on a separate substrate. Confirmation should include repeated sections and, where relevant, more than one position in the working envelope. The process window shall then be challenged using representative walls or features because stable single tracks do not demonstrate acceptable multilayer thermal behaviour.

9 Manufacturing of reinforcement structures

9.1 Surface preparation

Before deposition, the substrate surface shall be inspected and prepared using a documented sequence. The procedure shall define removal of oils, loose oxides, residues and coatings that could impair melt-pool stability or bonding. The interval between preparation and deposition shall be controlled. Surface preparation shall not introduce unacceptable thinning, deep scratches, or contamination. The set-up verification is as follows:

- verify substrate identity, thickness and orientation;
- verify powder batch and feeder condition;
- verify nozzle condition and alignment of laser, powder focus and programmed path;
- verify shielding and atmosphere before laser exposure;
- verify work offset, stand-off distance and collision clearance;
- record clamping and thermal contact conditions;
- execute a start-up or witness track where required.

9.2 Thin-wall strategy

Thin aluminium walls shall not be manufactured by repeated identical tracks without considering the change in heat dissipation with increasing build height (Figure 4). Progressive heat accumulation can cause widening, loss of layer height, lateral spray and geometric instability (Figure 5). The number and offset of tracks per layer, programmed layer increment, deposition direction and dwell time shall therefore be developed as a coupled strategy for the target cross-section.

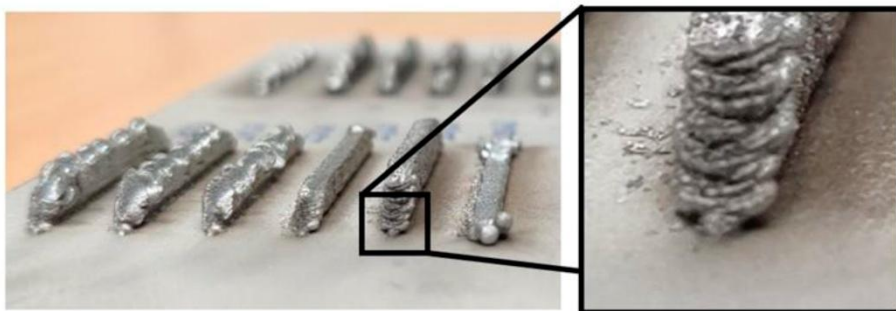


Figure 4 — Widening effect of the melt pool visible by the eyes

A comparable transition strategy shall be developed for each target cross-section. The number and offset of tracks, layer height, direction sequence, and dwell time shall be qualified together. The programmed layer increment shall be confirmed against the measured build height.

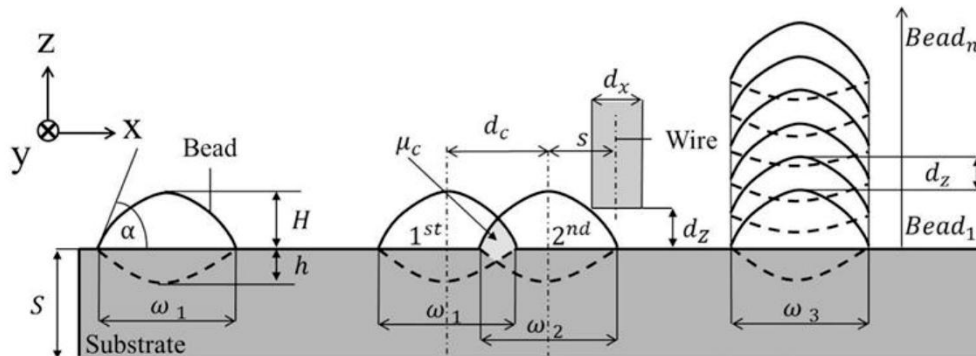


Figure 5 — Schematic representation of the geometrical parameters in DED processes

Intersections modify local heat input and powder overlap and shall therefore be separately qualified. The deposition sequence, path offset, and local dwell shall be defined. Cross-sections shall include the intersection and adjacent straight regions (Figure 6). Curved tracks and terminations shall be checked for overbuild, underbuild, lack of fusion, local dilution and distortion.

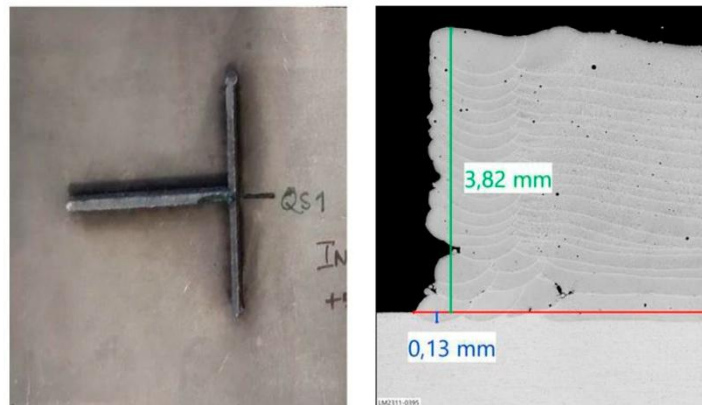


Figure 6 — Representative crossing-wall geometries used to qualify multilayer deposition strategies

At minimum, the operator shall record interruptions, visible instability, spatter or lateral spray, powder-feed interruption, abnormal plume, shielding alarms, collisions and evidence of overheating. If monitoring signals are available, their units, sampling rate, synchronisation and decision rules shall be documented. Monitoring does not replace post-process verification unless a validated correlation to the relevant quality characteristic has been established.

The manufacturing plan shall define whether interruption and restart are permitted. If permitted, the restart zone, cleaning, overlap, re-establishment of atmosphere and inspection shall be specified and qualified. Unplanned interruptions in critical regions shall be treated as deviations and assessed before testing or use.

The programmed layer height, number of tracks per layer, in-layer hatch or offset, deposition direction and inter-pass delay shall be developed as a coupled strategy. Aluminium walls experience a progressive reduction in heat-sink capacity as height increases. Consequently, an unchanged toolpath can create increasingly wide and shallow beads, lateral spray, and loss of geometric control.

In the informative reference-wall example, the lower layers were used to create a sufficiently wide foundation, and the upper layers were progressively reduced to a single track (Figure 7). This 3-2-1 sequence is an example, not a universal prescription. For another target section, the sequence shall be re-established from measured build height and width.

- Produce trial walls with sufficient length to distinguish start, steady-state, and termination regions.
- Measure wall height and width along the build, not only at one section.
- Section the wall at locations representative of stable deposition and of visible anomalies.
- Compare programmed layer increment with the actual increase in wall height.
- Inspect lateral spray and overhangs that can affect dimensional tolerance or become crack initiators.
- If dwell time is used, record its location and duration and verify that it does not create start-stop defects.

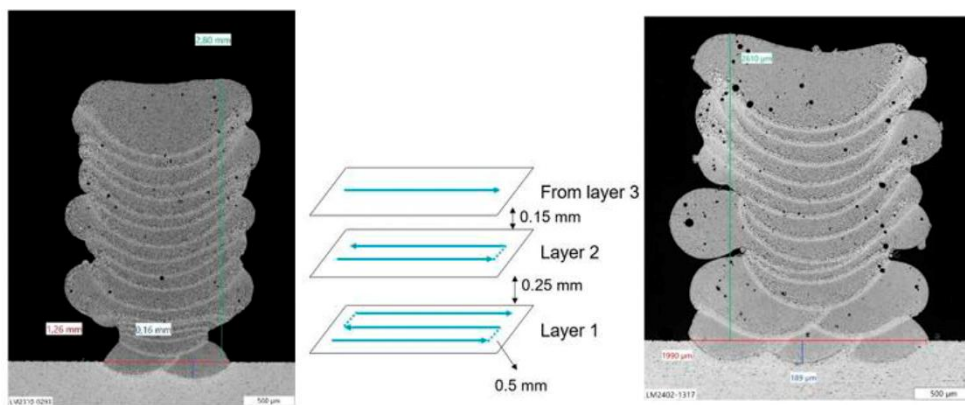


Figure 7 — Representative thin-wall specimens used to qualify multilayer deposition strategies

The energy and powder transients at the beginning and end of a track can generate underbuild, excess material or incomplete bonding. Qualification shall therefore define lead-in and lead-out positions, laser and powder timing, acceleration zones and whether starts and stops may occur in structurally critical regions. Where tracks intersect, the deposition order and local offset shall be fixed in the manufacturing file. On the other side, a manufacturing traveller should accompany each coupon or component. It shall identify the approved toolpath revision, parameter set, material batches, fixture, atmosphere history, operator, start and finish times, process interruptions, observed anomalies, post-processing and inspection status. Deviations shall remain linked to the physical item through a unique identifier.

10 Post-processing, inspection and quality assurance

10.1 Inspection planning and sampling

Inspection shall be planned before manufacturing so that destructive sections do not remove the only specimen required for mechanical validation. The plan shall identify critical locations from the design and process analyses, including thin substrate regions, changes in curvature, track starts and stops, intersections, highly constrained zones and locations predicted to experience high tensile strain.

Inspection method	Purpose	Important limitation
Visual inspection	Detect gross discontinuity, oxidation, spray, surface cracks and incomplete paths.	Cannot demonstrate absence of subsurface lack of fusion or porosity.
Dimensional measurement / 3D scan	Quantify reinforcement position, dimensions and component distortion.	Result depends on datum definition, filtering and accessibility.
Metallography	Directly assess fusion, dilution, HAZ and local defects.	Destructive and two-dimensional; location selection is critical.
Computed tomography	Assess volumetric defects where geometry and resolution permit.	Detectability depends on thickness, defect size, orientation and scan settings.
Surface NDT	Screen for surface-breaking discontinuities with a qualified method.	May have limited applicability on rough as-deposited surfaces.

10.2 Visual, dimensional and quality inspection

The component shall be allowed to cool under controlled conditions before unclamping. The cooling conditions and the time to unclamping shall be recorded, as premature release from the fixture can modify the final distortion state. Dimensional inspection shall be performed after the component has reached a stable temperature and shall be repeated after any heat treatment, machining or surface-finishing operation that can alter the reinforcement or component geometry.

Visual inspection shall identify discontinuous tracks, incomplete intersections, adherent powder, lateral spray, oxidation, surface cracks and interface separation. Dimensional inspection shall include, where applicable, reinforcement width, height, length and position, gap spacing and component distortion. The measurement method, equipment, resolution, datum system and alignment procedure shall be reported. Distortion shall be determined relative to the pre-deposition geometry or nominal CAD geometry using a declared datum and registration method. The selected method shall distinguish relevant component deformation from rigid-body displacement. Because fixturing, substrate thickness, deposited geometry, thermal history and unclamping conditions can affect the measured displacement, acceptance limits shall be component-specific and related to assembly, dimensional and mechanical-function requirements.

Metallographic sections shall be selected at representative and critical locations, including track starts and terminations, steady-state regions, intersections, curves, layer transitions and suspected defects. The location and orientation of each section shall be traceable to the deposited path. Metallographic examination should determine or describe track geometry, penetration or dilution, porosity, lack of fusion, interface continuity and the extent of the heat-affected zone. Where non-destructive examination is applied, the selected method shall be justified with respect to the expected defect type, size and orientation, as well as the material thickness and component geometry. Detection capability shall be demonstrated using suitable reference features or correlation with destructive sectioning. The absence of an indication shall not be interpreted as evidence of the absence of defects below the demonstrated detection limit.

Acceptance criteria shall be established by the responsible organisation for the intended application. The acceptance decision shall consider, as applicable, reinforcement geometry and position, penetration or dilution, lack of fusion, porosity, cracking, interface continuity, heat-affected zone, component distortion and the results of mechanical validation. Each nonconformance shall be documented and assigned an appropriate disposition: acceptance as-is with technical justification, repair using a qualified procedure, rework, rejection or further investigation.

10.3 Mechanical characterisation at specimen scale: three-point bending

Where representative tensile specimens cannot be extracted from the deposited reinforcement, three-point bending may be used to compare the mechanical response of the unreinforced substrate with that of hybrid specimens in which the reinforcement is loaded predominantly in tension or compression. The method is intended for comparative evaluation of the complete hybrid configuration, including the substrate, deposited reinforcement, reinforcement root and interface. The resulting force, stiffness and energy values shall therefore be regarded as specimen-level responses and shall not be interpreted directly as intrinsic material properties or transferable design allowables.

The test series should comprise, as a minimum, an unreinforced reference specimen and reinforced specimens tested with the deposited feature located respectively on the tensile and compression surfaces. The substrate material, temper, orientation, thickness and surface condition shall be equivalent for all configurations. The reinforcement position relative to the tensile and compression surfaces shall be stated explicitly because the loading orientation can substantially modify the force-displacement response and the governing failure mechanism.

For thin aluminium substrates, a rectangular coupon approximately 150 mm long, 20 mm wide and 1.5 mm thick may be used as a starting geometry (Figure 8). A representative straight reinforcement may have a deposited length of approximately 110 mm, a width of approximately 2 mm and a height of approximately 2.5 mm. These dimensions are suitable for comparative testing of small DED-LB/P features but shall be adapted when they do not reproduce the relative substrate thickness, reinforcement dimensions or root geometry of the intended component. The reinforcement should be centred along the specimen width and should extend symmetrically with respect to the midspan. Its termination should remain outside the region of maximum bending moment where the purpose of the test is to evaluate the steady-state reinforcement section rather than the track termination. If initiation from the reinforcement start or end is of interest, a separate specimen configuration should be defined.

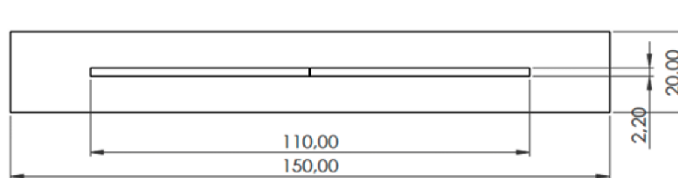


Figure 8 — Flat specimen with reinforcement for bending tests — The dimensions are expressed in mm

A support span of approximately 52 mm may be used for the stated coupon geometry (Figure 9). More generally, the span should be selected to generate a bending-dominated response while limiting excessive local indentation and transverse shear. As an initial recommendation, the ratio between support span, L , and substrate thickness, t , should be sufficiently large to avoid a shear-dominated response, while the specimen should extend beyond each support by enough distance to prevent the specimen ends from affecting the measured behaviour. The same support span shall be used for the reference, tensile-side and compression-side configurations. The loading nose and support rollers should have identical diameters for all tests and rounded contact surfaces that do not introduce premature local damage. Roller diameters in the approximate range of 8 mm to 12 mm are suitable as an initial arrangement for a 1.5 mm-thick aluminium coupon, provided that local indentation is checked after testing. The selected dimensions shall be reported and justified for the tested geometry.

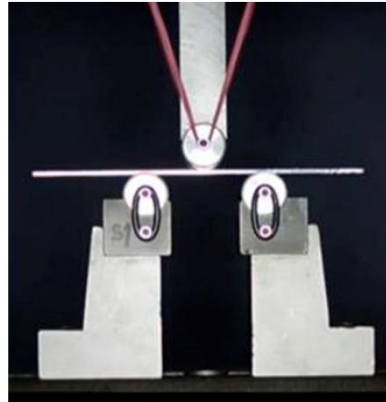


Figure 9 — Test machine for 3-point bending test with a specimen without reinforcement

The reinforcement geometry shall be measured before testing. At minimum, the report shall include the actual substrate thickness, specimen width, reinforcement height and width, reinforcement length, lateral offset from the specimen centreline and longitudinal position relative to the loading nose and supports. The reinforcement-root profile should also be characterised where the local geometry can act as a stress concentrator. Initial out-of-plane distortion shall be measured when it can affect specimen seating, loading symmetry or comparison between configurations. Specimens showing visible cracks, incomplete deposition, interface separation, severe misalignment or dimensional deviations outside the specified range shall be documented and assessed before testing; they shall not be excluded without a stated technical criterion.

The test fixture shall comprise two parallel supports and a centrally positioned loading nose. The specimen shall be placed symmetrically on the supports, with the reinforcement facing downwards when tensile loading of the reinforcement is required and upwards when compression loading is required. Alignment shall minimise torsion, lateral movement and eccentric loading. The supports should be free to rotate where required to minimise friction, and the loading nose shall remain aligned with the centre of the support span. The specimen shall be brought into contact with the loading nose using a low preload that removes clearance without causing measurable plastic deformation or damage.

Testing should be performed under monotonic displacement control. For the reference geometry described above, a crosshead displacement rate of up to approximately 80 mm/min is recommended for quasi-static comparative characterisation. If a different rate is selected, it shall be kept constant across all configurations and shall be sufficiently low to avoid dynamic effects unless rate sensitivity is an intended part of the assessment. The use of 80 mm/s would correspond to a substantially higher loading-rate regime and should not be described as quasi-static; such a rate would require suitable high-rate instrumentation and explicit justification. Force and displacement shall be recorded continuously at a sampling frequency sufficient to resolve the initial response, first cracking, abrupt load drops, maximum force and post-cracking behaviour. Where machine crosshead displacement is used, the influence of machine and fixture compliance shall be evaluated. An independent displacement measurement method, video recording or digital image correlation should be used when accurate local deformation, crack initiation or reinforcement-interface separation needs to be identified.

The test shall continue to a predefined displacement or until a declared termination criterion is reached. A maximum central displacement of approximately 30 mm may be used for the suggested coupon and span where the fixture permits this displacement without interference or loss of valid contact. Energy should be evaluated at common intermediate displacement levels, for example 10 mm, 20 mm and 30 mm, provided that all compared specimens reach those values. A test shall be terminated earlier if the specimen leaves the supports, the fixture interferes with the reinforcement, the force or displacement range is exceeded, or the recorded response is no longer representative of three-point bending.

The force-displacement curve shall be reported for every individual specimen (Figure 10). Initial flexural stiffness may be obtained from a linear fit over a declared displacement interval after excluding seating effects and before significant plasticity or damage. The fitting interval and coefficient of determination should be reported, but the calculated slope shall be described as the stiffness of the tested specimen-fixture configuration rather than as a material modulus. Maximum force, displacement at maximum force, force and displacement at first visible cracking, and any significant load drop should also be determined where identifiable.

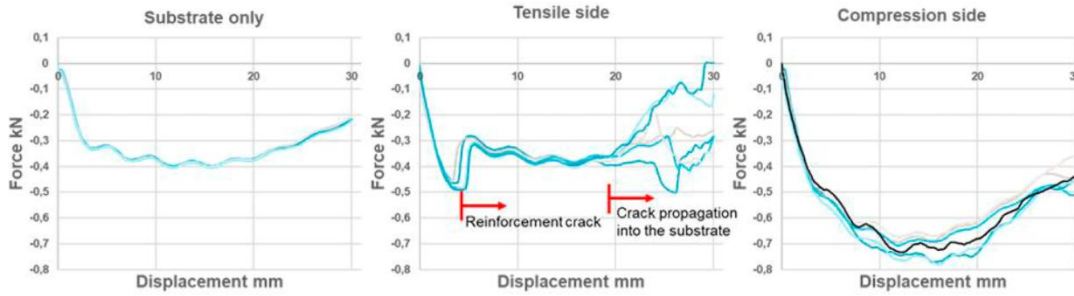


Figure 10 — Representative force-displacement curve for specimens with and without reinforcements

The absorbed energy up to a specified displacement, δ_i , shall be calculated from:

$$E(\delta_i) = \int_0^{\delta_i} F(\delta) d\delta \quad (1)$$

where $F(\delta)$ is the measured force and δ is the measured displacement. Force shall be expressed in newtons and displacement in metres when energy is reported in joules. If displacement is processed in millimetres, the corresponding unit conversion shall be applied. The integration method, zero correction, displacement limits and treatment of unloading or signal oscillation shall be stated. Energy values shall only be compared when they have been integrated over the same displacement interval.

The specimen shall be inspected during and after testing to identify cracking within the deposited reinforcement, cracking at the reinforcement root, reinforcement-substrate separation, substrate cracking, local indentation and contact-related damage. The crack location and orientation shall be related to the reinforcement geometry and loading condition. Particular attention shall be paid to whether cracking initiates within the deposited material, at a geometric stress concentration, at a lack-of-fusion defect, within the heat-affected substrate or along the interface. Representative photographs shall show the tensile surface, compression surface, reinforcement root and final specimen shape. Metallographic examination or fractography should be performed when visual examination cannot distinguish between reinforcement fracture, interface separation and failure through the substrate.

The test report shall include the material and manufacturing history, specimen and reinforcement dimensions, reinforcement orientation, support span, roller and loading-nose diameters, loading rate, preload, acquisition frequency, displacement measurement method and termination criterion. For each specimen, the report shall provide the individual force-displacement curve, absorbed energy over the specified displacement intervals, initial stiffness where determined, maximum force, visible cracking, crack location, interface separation and final shape. The number of specimens and the scatter between nominally equivalent specimens shall also be reported. A test shall be considered invalid when the response is materially affected by specimen slip, incorrect orientation, eccentric loading, fixture interference, sensor saturation, loss of data or failure outside the intended test region. Invalid results shall remain in the test record together with the technical justification for their exclusion.

An increase in force, stiffness or absorbed energy shall not by itself be interpreted as improved structural performance. The corresponding peak force, deformation mode, cracking behaviour and interface integrity shall also be considered. Final conclusions shall distinguish between observations obtained directly from the test, interpretation of the governing failure mechanism and implications for the component-level reinforcement design.

10.4 Mechanical characterisation at specimen scale: fracture assessment

Fracture assessment at specimen scale should distinguish between the fracture behaviour of the thin aluminium substrate and that of the deposited reinforcement. Different procedures may be required because the substrate can generally be machined into standard or pre-cracked specimens, whereas the deposited feature can be too small to permit extraction of a representative specimen or introduction of a fatigue pre-crack. Results obtained using different specimen types and crack-preparation procedures shall therefore not be treated as directly equivalent.

For thin ductile substrate materials, the Essential Work of Fracture, EWF, method may be applied using double-edge-notched tensile, DENT, specimens in accordance with CWA 17793:2021. The method is suitable for thin specimens in which conventional plane-strain fracture-toughness conditions cannot normally be achieved. The result characterises the fracture response of the tested sheet or thin substrate under predominantly plane-stress conditions and is thickness-dependent [3]. Substrate thickness, material orientation, temper, surface condition and manufacturing history shall therefore be reported with the result.

The DENT specimen (Figure 11) shall contain two opposing notches positioned symmetrically on the specimen centreline, leaving an uncracked ligament of initial length l_0 . The specimen width and ligament range shall be selected so that fully yielded ligament conditions can be achieved before crack propagation, while the plastic deformation remains sufficiently localised around the ligament for the EWF assumptions to remain applicable. A series of specimens with different ligament lengths shall be tested. The ligament range shall include enough valid values to determine the relationship between the specific work of fracture and the initial ligament length without relying on extrapolation from a narrow interval.

As an initial recommendation for thin aluminium substrates with a thickness of approximately 1.0 mm to 2.0 mm, rectangular DENT specimens may have an overall width of approximately 40 mm and a gauge length sufficient to maintain uniform tensile loading outside the notched region. Ligament lengths may initially be selected within approximately 5 mm to 15 mm, provided that the applicable dimensional and validity requirements of CWA 17793:2021 are satisfied. At least three different ligament lengths should be investigated, with multiple specimens tested for each ligament length. These dimensions are indicative and shall be adapted to the material thickness, ductility, available substrate dimensions and applicable standard requirements.

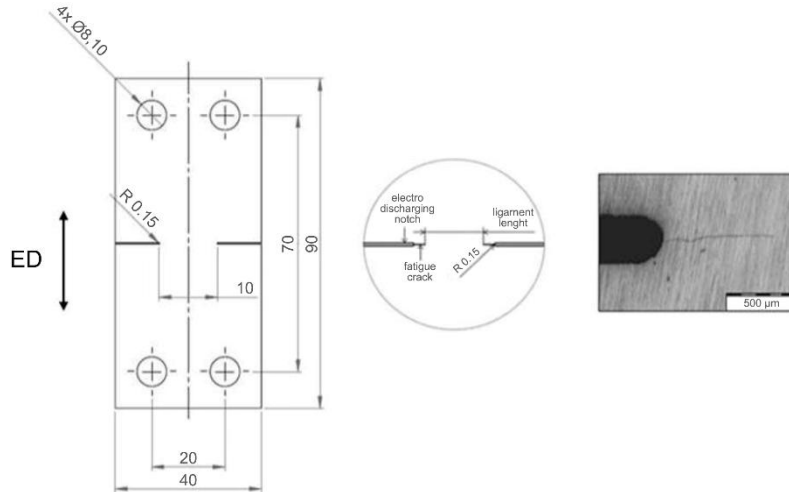


Figure 11 — DENT specimen geometry and detail of the fatigue pre-crack at the notch root — ED: Extrusion direction — The dimensions are expressed in mm

The notches shall be introduced symmetrically and shall terminate in fatigue pre-cracks or another crack preparation accepted by the applicable method. The initial ligament length shall be measured after pre-cracking and before testing. The measurement procedure and resolution shall be reported. Notch asymmetry, crack curvature or a significant difference between the two crack lengths can create eccentric loading and invalidate the assumed ligament condition. The specimen shall be loaded monotonically in tension using aligned grips that minimise bending and specimen rotation. A constant crosshead or displacement rate shall be applied to all specimens included in the comparison. The selected rate shall be sufficiently low to avoid unintended dynamic effects unless loading-rate sensitivity is being investigated explicitly. Force and displacement shall be recorded continuously until complete ligament fracture. The acquisition rate shall be sufficient to identify yielding, maximum force, crack initiation and final loss of load-carrying capacity. Displacement should be measured across the specimen gauge region or notched ligament using an extensometer, optical measurement system or digital image correlation. Crosshead displacement may be used only where machine and grip compliance do not materially affect the calculated work of fracture or where an appropriate compliance correction is applied. The displacement measurement method shall remain unchanged for all ligament lengths included in the EWF analysis. Digital image correlation is recommended to verify the deformation conditions around the ligament. The strain field should demonstrate that the ligament has yielded before crack initiation and that plastic deformation develops in a consistent region surrounding the crack plane. The DIC field of view shall include both notch tips and the complete ligament. Camera calibration, image resolution, subset or facet size, step size, acquisition frequency and strain-processing procedure shall be reported when DIC results are used to support test validity.

The total work of fracture, W_f , shall be calculated as the area under the force-displacement curve up to complete ligament fracture:

$$W_f = \int_0^{u_f} F(u) du \quad (2)$$

where $F(u)$ is the measured force, u is the measured displacement and u_f is the displacement at complete fracture. Force shall be expressed in newtons and displacement in metres when work is reported in joules. The integration method, signal-zero correction, endpoint definition and treatment of unloading or signal oscillations shall be stated. According to the EWF approach, the total work of fracture is separated into the essential work required to create new fracture surfaces and the non-essential plastic work dissipated in the surrounding plastic region. For a specimen with initial ligament length l_0 and thickness t , the total work may be expressed as:

$$W_f = w_e l_0 t + \beta w_p l_0^2 t \quad (3)$$

where w_e is the specific essential work of fracture, w_p is the specific non-essential plastic work and β is a geometric factor related to the shape of the plastic zone. Dividing by the ligament area gives:

$$w_f = \frac{W_f}{l_0 t} = w_e + \beta w_p l_0 \quad (4)$$

The specific total work of fracture, w_f , shall be plotted against the initial ligament length, l_0 . The intercept of a valid linear fit gives the specific essential work of fracture, w_e , while the slope represents the product βw_p . The fitting method, number of specimens, ligament range, coefficient of determination, residuals and confidence intervals should be reported. A high coefficient of determination alone shall not be considered sufficient evidence of validity if the specimens exhibit inconsistent deformation or fracture mechanisms. Force-displacement curves should have geometrically similar shapes across the selected ligament range. Specimens showing asymmetric crack propagation, fracture outside the ligament, incomplete ligament yielding, excessive necking outside the fracture region, grip slip or invalid displacement measurements shall be identified. Exclusion shall be based on declared technical or standard-based criteria, and all excluded results shall remain traceable in the test record. The EWF result is dependent on thickness and deformation state. Values obtained from substrates with different thicknesses, tempers, orientations or loading rates shall not be combined without justification. The reported w_e shall not be designated as a plane-strain fracture-toughness value and shall not be directly equated to K_{IC} . Any comparison with J-based or stress-intensity-based toughness parameters shall describe the different specimen constraints, crack preparation and validity conditions.

Direct application of the EWF method to a small deposited reinforcement may not be practicable because the reinforcement dimensions can be insufficient to machine a DENT specimen with several ligament lengths. Extraction of a separate fracture specimen can also remove the representative substrate constraint, thermal history, root geometry and interface condition. In this situation, a notched three-point bending test may be used to obtain a comparative fracture indicator for the deposited feature. The comparative bending specimen should retain the deposited reinforcement on its original substrate wherever the reinforcement-substrate interaction is part of the assessment. A straight reinforcement should be positioned along the specimen centreline and aligned with the loading direction. A notch shall be introduced into the reinforcement at the location subjected to the maximum bending moment. The notch should be centred beneath the loading nose unless another position represents the intended component condition more accurately.

For a hybrid coupon approximately 150 mm long, 20 mm wide and 1.5 mm thick, with a deposited reinforcement approximately 110 mm long, 2 mm wide and 2.5 mm high, a support span in the approximate range of 25 mm to 35 mm may be considered for local fracture assessment of the reinforcement (Figure 12). A span of approximately 29 mm provides a suitable initial configuration for this specimen size, subject to verification that the response is bending-dominated and that the supports do not interfere with the deposited feature. Loading-nose and support-roller diameters of approximately 8 mm to 12 mm may be used, provided that local indentation does not control the response.

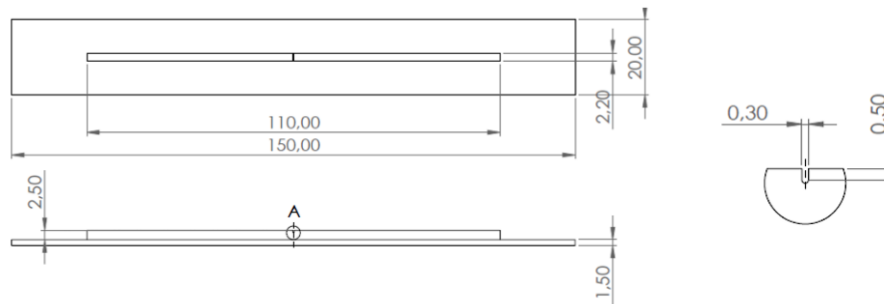


Figure 12 — Flat specimen with reinforcement for fracture toughness tests

The notch should be introduced using electrical discharge machining or another controlled machining method capable of producing a reproducible notch without excessive mechanical deformation or thermal damage. Comparative notch depths of approximately 0.5 mm and 1.0 mm may be investigated for a reinforcement height of approximately 2.5 mm, provided that a sufficient residual ligament remains and the notch does not penetrate into the substrate. The actual notch depth and remaining ligament shall be measured for every specimen. The notch-root radius, notch width, machining method and notch orientation shall be reported because they directly influence the local stress concentration and measured fracture response.

The notch shall not be described as a crack unless a fatigue pre-crack has been introduced and verified. A machined or EDM notch has a finite root radius and does not reproduce the stress field associated with a sharp fatigue crack. Results from notched reinforcement specimens shall therefore be reported as comparative fracture-initiation or fracture-resistance indicators. The use of K_Q , J_Q or another provisional parameter shall be accompanied by an explicit statement that the result does not constitute valid K_{IC} or J_{IC} unless all specimen geometry, pre-cracking, constraint and validity requirements of the applicable fracture standard are satisfied.

The notched specimen shall be positioned symmetrically on the supports, with the reinforcement located on the tensile surface unless compression-side behaviour is specifically under investigation (Figure 13). Locating the notched reinforcement on the tensile side promotes opening of the notch and facilitates comparison of fracture initiation. The notch plane shall be aligned with the loading nose and the centre of the support span. Alignment shall be verified before loading because an offset between the notch and loading nose can introduce mixed-mode loading and additional scatter.



Figure 13 — Fracture toughness test setup for reinforcement and strain at fracture initiation for the reinforcement with a notch of 0.5 mm

The test should be performed under monotonic displacement control. For the indicative coupon and span described above, a displacement rate of approximately 1 mm/min may be used as an initial quasi-static condition. The same rate shall be applied to all specimens included in the comparison. Force and displacement shall be recorded continuously until fracture of the reinforcement, substrate failure, complete loss of load-carrying capacity or a predefined maximum displacement. The acquisition rate shall be sufficient to resolve the maximum force and abrupt load drops associated with crack initiation or unstable propagation. An unreinforced substrate specimen and an unnotched reinforced specimen should be tested using the same span, roller geometry and loading rate. The unreinforced specimen establishes the substrate contribution, while the unnotched reinforced specimen establishes the response of the hybrid coupon without an introduced stress concentrator. Testing more than one notch depth can support interpretation of the effect of the remaining ligament but shall not be used to extrapolate a standard fracture-toughness value unless a validated fracture-mechanics procedure is available.

The report shall include the individual force-displacement curve, maximum force, displacement at maximum force, force and displacement at the first significant load drop, absorbed energy up to defined displacement or fracture points, notch depth, remaining ligament, crack path and final specimen shape. Where practical, video recording or DIC should be used to identify crack initiation and to determine whether the crack propagates through the deposited reinforcement, along the reinforcement-substrate interface or into the substrate.

Post-test examination shall document the notch root, crack-initiation location, propagation path, interface condition and final fracture surface. Metallography or fractography should be used where visual examination cannot distinguish between fracture through deposited material, lack of fusion, interfacial separation and cracking of the heat-affected substrate. The presence of porosity, lack of fusion or an irregular reinforcement root shall be reported because these features can control the measured response independently of the nominal notch geometry. The number of specimens shall be selected according to the intended comparison. Individual results and scatter shall be reported. A limited specimen series may support relative comparison between notch depths, material conditions or deposition strategies, but it shall not be used to establish material allowables or statistical fracture resistance. Tests affected by specimen slip, notch misalignment, fixture interference, sensor saturation, failure outside the intended region or dimensions outside the declared tolerance shall be identified as invalid. The reason for invalidation shall remain in the test record.

The final assessment shall clearly distinguish between values obtained using pre-cracked DENT specimens and indicators obtained using notched bending specimens. The EWF result characterises the thickness-dependent fracture response of the thin substrate under the validity conditions of CWA 17793:2021. The notched bending result characterises the response of a specific deposited-feature geometry, notch configuration, interface and substrate constraint. The two results may be used together to identify whether fracture resistance is governed primarily by the substrate, deposited reinforcement, interface or local geometry, but they shall not be presented as interchangeable fracture-toughness measurements.

10.5 Mechanical characterisation at specimen scale: fatigue assessment

Fatigue assessment at specimen scale shall reproduce, as far as practicable, the loading mode, reinforcement orientation and critical stress state expected in the component. For deposited reinforcements on thin aluminium substrates, this requires particular attention to the reinforcement root, reinforcement-substrate interface and heat-affected substrate, as these regions can govern crack initiation even when the deposited reinforcement increases the initial stiffness of the hybrid specimen. The test configuration shall therefore be selected to evaluate the complete hybrid response rather than the deposited material in isolation.

Where the deposited feature is too small to extract a representative axial fatigue specimen, three-point bending may be used for rapid comparative assessment. The method allows an unreinforced substrate to be compared with hybrid specimens while retaining the as-deposited reinforcement geometry, interface, root profile and local thermal history. The reinforcement shall be placed on the tensile surface when the objective is to evaluate crack initiation at the reinforcement root or interface. A compression-side configuration may also be tested when that loading state is relevant to the intended component, but the two orientations shall be reported and interpreted separately.

For thin aluminium substrates, a rectangular coupon approximately 150 mm long, 20 mm wide and 1.5 mm thick may be used as an initial specimen geometry (Figure 8). A representative straight reinforcement may have a deposited length of approximately 110 mm, a nominal width of approximately 2 mm and a nominal height of approximately 2.5 mm. The reinforcement should be centred along the specimen width and positioned symmetrically relative to the support span. These dimensions are suitable for comparative testing of small DED-LB/P reinforcements but shall be adapted where they do not reproduce the relative substrate thickness, reinforcement dimensions, root geometry or loading condition of the intended component.

The support span should generate a bending-dominated response while avoiding excessive local indentation and transverse shear. For the indicative specimen geometry, a support span of approximately 50 mm to 55 mm may be used, with 52 mm as a suitable initial value. The loading nose and support rollers should have rounded contact surfaces and diameters in the approximate range of 8 mm to 12 mm, provided that local indentation or contact fatigue does not control the test. The same span, rollers, loading nose and specimen positioning shall be used for the unreinforced and reinforced configurations.

The specimen shall extend sufficiently beyond both supports to maintain stable contact throughout the test. The reinforcement terminations should remain outside the region of maximum bending moment when the purpose is to evaluate the steady-state reinforcement section and root. If fatigue initiation at the reinforcement start or termination is relevant, a separate specimen configuration shall be defined and shall not be combined with results from centrally reinforced specimens.

The test series shall include, as a minimum, an unreinforced reference specimen and a reinforced specimen manufactured from an equivalent substrate material, thickness, orientation and surface condition. An unreinforced reference is necessary to determine whether changes in the measured fatigue response arise from the deposited reinforcement or from the intrinsic fatigue behaviour of the substrate. Where the reinforcement can experience both tension and compression during service, separate specimens should be tested with the reinforcement located on the tensile and compression surfaces.

Before testing, the substrate thickness, specimen width, reinforcement width, height and position shall be measured. The reinforcement-root geometry and initial out-of-plane distortion should also be characterised where these quantities can affect the local stress concentration or specimen seating. Specimens shall be visually inspected for incomplete deposition, visible cracks, misalignment, interface separation, excessive lateral spray and dimensional deviations. A specimen shall not be excluded solely because it contains a manufacturing imperfection unless the applicable rejection criterion was established before testing. Where a specimen is excluded, the reason shall remain in the test record.

The specimen shall be positioned symmetrically on two parallel supports, with the central loading nose aligned with the middle of the support span. Alignment shall minimise lateral movement, specimen torsion and eccentric loading. The reinforcement shall be positioned directly beneath the loading nose when it is located on the tensile surface, unless another position is required to reproduce the intended component loading. The loading nose shall be brought into contact using a low preload that removes clearance without introducing significant fatigue damage or plastic deformation.

The test system shall apply a cyclic force under closed-loop control. Force-controlled loading is preferred for a stepwise fatigue assessment because the maximum and minimum loads can be defined directly for each block. The force ratio shall be calculated as:

$$R_F = \frac{F_{min}}{F_{max}} \quad (5)$$

where F_{min} and F_{max} are respectively the minimum and maximum applied forces in each cycle. If the test is reported in terms of nominal bending stress, the corresponding stress ratio shall be defined as:

$$R_F = \frac{\sigma_{min}}{\sigma_{max}} \quad (6)$$

The report shall state clearly whether the applied levels are expressed as force or nominal stress. Force ratio and stress ratio shall not be used interchangeably unless the relation between force and stress remains linear and the same stress definition is used throughout the test.

For comparative screening of the proposed hybrid coupons, a positive load ratio such as $R_F=0.1$ may be used to maintain contact between the specimen and the loading system throughout the cycle. A test frequency of approximately 10 Hz to 20 Hz may be selected, with 15 Hz as a suitable initial value, provided that specimen heating, dynamic amplification and loss of contact are negligible. The temperature should be monitored during preliminary tests when cyclic heating is possible. If the specimen temperature increases sufficiently to affect material behaviour or displacement response, the frequency shall be reduced or an appropriate cooling and dwell strategy shall be introduced.

A stepwise loading procedure in accordance with the principles of CWA 18107-2:2024 may be used for rapid comparative screening (Figure 14) [4]. The test shall begin at a maximum force below the expected fatigue-damage transition. For the indicative specimen and fixture, an initial maximum force of approximately 100 N may be used as a starting value, subject to verification that the corresponding response is stable and does not produce immediate visible cracking or significant plastic deformation. The initial force shall be adapted when the substrate thickness, span, reinforcement geometry or material condition differs from the indicative configuration. The cyclic loading shall be applied in blocks containing a predefined and constant number of cycles. A block length of approximately 6 000 cycles may be used for rapid screening. After completion of each block, the maximum force may be increased by a constant increment, for example 25 N, while maintaining the selected force ratio. The increment shall be sufficiently small to identify a change in fatigue response without causing the transition to be crossed in a single excessively large step. The initial maximum force, block length and force increment shall remain constant for all specimens included in the comparison. A constant diagnostic load shall be applied between successive fatigue blocks to monitor the evolution of the specimen response. For the indicative configuration, a diagnostic maximum force of approximately 200 N may be used, provided that the diagnostic cycle does not itself cause significant additional damage or plastic deformation before the relevant transition. The diagnostic load shall remain unchanged throughout the test and shall be selected so that the corresponding displacement is measurable with adequate resolution.

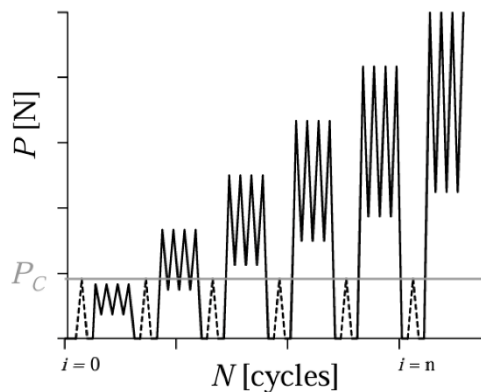


Figure 14 — Stepwise loading blocks used until fracture of the specimen

The displacement associated with the diagnostic load shall be measured after each fatigue block using the same loading sequence, acquisition window and data-processing procedure. The report shall state whether displacement, compliance or stiffness is used as the diagnostic quantity. Values based on crosshead displacement include the compliance of the machine and fixture and shall therefore be regarded as system-level indicators unless machine compliance has been corrected. An independent displacement transducer or optical measurement method should be used when the expected changes are small relative to machine compliance. The diagnostic procedure shall minimise the influence of transient effects. Displacement should be extracted from a defined point or averaged over a declared number of diagnostic cycles. The same procedure shall be used after every fatigue block. If the test is paused before the diagnostic cycle, the pause duration shall be controlled because viscoplastic recovery, thermal stabilisation or seating effects can modify the measured displacement independently of fatigue damage.

The diagnostic displacement, compliance or stiffness shall be plotted against the maximum force applied in each preceding fatigue block. At relatively low force levels, the diagnostic response may follow an approximately stable trend. The onset of accelerated displacement increase or stiffness reduction can indicate the development of fatigue damage, crack initiation, local plasticity or evolving interface separation. The characteristic transition may be identified from a change in slope between two fitted regions of the diagnostic-response curve. The procedure used to identify the transition shall be defined before comparing specimen configurations. A graphical intersection of two linear fits, a segmented regression procedure or another objective change-point method may be used. The selected fitting intervals, number of points, residuals and goodness-of-fit measures should be reported. The transition shall not be selected solely by visual judgement when the result is used to rank materials or reinforcement configurations.

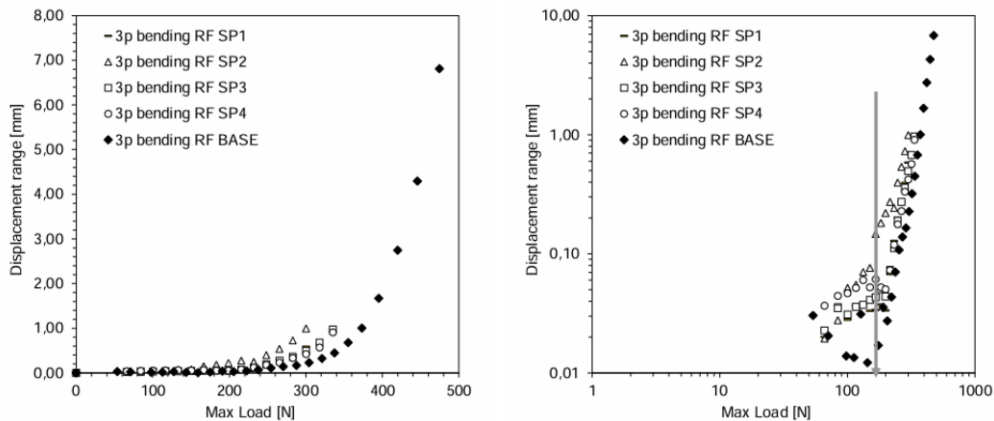


**Figure 15 — Representative displacement vs. load curves represented in linear and log plots —
The grey arrow indicates the change in slope**

The characteristic force, F_f , shall be determined from the change in slope of the diagnostic displacement, compliance or stiffness response. Where results are expressed as nominal bending stress, the calculation method shall be reported. For an unreinforced rectangular specimen under central three-point bending, the maximum nominal outer-fibre stress may be estimated as:

$$\sigma_{max} = \frac{3F_{max}L}{2bt^2} \quad (7)$$

where F_{max} is the maximum applied force, L is the support span, b is the specimen width and t is the substrate thickness. This equation assumes a homogeneous rectangular section and shall not be applied directly to a reinforced specimen. For hybrid specimens, the result shall be identified either as the nominal substrate stress, calculated without considering the reinforcement, or as a stress obtained using a validated composite-section or finite-element model. The same stress definition shall be used for all compared configurations. Testing shall continue until a predefined termination condition is reached, such as visible cracking, a specified change in diagnostic response, specimen separation, loss of stable contact, excessive permanent deformation or the capacity limit of the test system. Force, displacement and cycle count shall be recorded throughout the test, including the actual number of cycles completed in each block and the loading history of interrupted tests.

Optical monitoring or periodic inspection may be used to identify crack initiation. After testing, the specimen shall be photographed and examined to determine whether cracking initiated in the substrate, deposited reinforcement, reinforcement root, heat-affected zone, interface or a manufacturing defect. Fractography or metallographic sectioning should be used where the initiation mechanism cannot be identified visually.

At least three nominally equivalent specimens per configuration are recommended for preliminary comparative screening, although this is insufficient to establish a statistical fatigue curve or design allowable. Individual results and diagnostic-response curves shall be reported. Tests affected by specimen slip, loss of contact, incorrect orientation, fixture interference, control instability, sensor saturation, excessive heating or failure outside the intended region shall be identified as invalid and retained with the reason for exclusion.

The report shall document the specimen and reinforcement geometry, loading configuration, force or stress ratio, frequency, block length, force increment, diagnostic load, displacement-measurement method, transition-identification procedure, termination criterion, characteristic force or stress, total cycle count and observed failure mechanism.

The stiffness-method transition is a comparative damage indicator specific to the tested geometry and loading sequence. It shall not be reported as a conventional fatigue or endurance limit unless supported by a validated correlation. Constant-amplitude testing remains necessary to establish S-N curves, run-out behaviour, survival probabilities, mean-stress effects or design allowables. Interpretation shall distinguish changes in global stiffness from the local fatigue mechanism, particularly when cracking initiates at the reinforcement root or interface.

10.6 Mechanical characterisation at component level: crash assessment

High-speed crash testing shall be used where inertia, strain-rate sensitivity, progressive folding, dynamic contact or rapid failure mechanisms materially affect the structural response. The test shall assess the complete hybrid component, including the substrate, deposited reinforcements, reinforcement roots, interfaces and heat-affected regions. Results shall therefore be reported as component-level responses of the tested configuration and not as intrinsic material properties.

The test programme shall include at least one unreinforced reference configuration and the reinforced configurations under assessment. All components shall have equivalent substrate material, temper, wall thickness, production route, initial geometry and boundary conditions. Differences unrelated to the reinforcement, including heat treatment, machining, initial imperfections or surface condition, shall be controlled or documented. The number of nominally equivalent components shall reflect the intended conclusion. At least three tests per configuration are recommended for preliminary comparative assessment, where manufacturing availability permits, although this number is insufficient to establish statistically based design allowables.

A rectangular or square thin-walled aluminium extrusion may be used as a representative crash-box geometry for axial compression. A component length of approximately 300 mm is suitable as an initial configuration, provided that the cross-section, wall thickness and target crush displacement allow several progressive folds to develop. The component length, unsupported length, cross-sectional dimensions, corner radii, wall thickness, end perpendicularity and initial geometric imperfections shall be measured and reported. Where the geometry does not represent a production component, the specimen shall be identified as a demonstrator. The reinforcement geometry shall reproduce the intended structural function and loading state. Longitudinal ribs, angled or fishbone tracks, transverse tracks, cellular features or combinations of these geometries may be considered (Figure 1). The report shall include reinforcement width, height, length and position, track spacing, gap length, intersection geometry, distance from the component ends and deposited mass. Gaps or unreinforced regions intended to initiate folding shall be manufactured at controlled positions. The reinforcement layout shall be evaluated over the complete deformation sequence because a feature initially loaded in compression can subsequently experience bending, tension or interface shear as folds develop.

Each component shall be visually and dimensionally inspected before testing. Inspection shall identify incomplete tracks, discontinuous reinforcement, surface cracks, oxidation, adherent powder, lateral spray and visible interface separation. Component straightness, wall thickness, reinforcement dimensions, gap spacing, end geometry and initial distortion shall be recorded. Components outside the declared tolerances shall be documented and assigned a disposition before testing.

The component shall be positioned between nominally rigid loading surfaces and subjected to axial compression using a test system capable of delivering the required impact velocity and displacement (Figure 16). The lower end shall be attached to a rigid reaction plate using a fixture that reproduces the intended boundary condition without suppressing the expected folding mechanism. The upper loading plate or impactor shall remain approximately perpendicular to the component axis at initial contact. Fixing method, plate geometry, friction condition and component orientation shall be reported. The component axis shall be aligned with the impact direction. Initial angular and lateral misalignment shall remain within declared tolerances because eccentric loading can change the fold sequence, peak force and failure location. Where the reinforcement layout is asymmetric, its orientation relative to the loading system and imaging equipment shall be controlled. An initial trigger may be used to control the position of the first fold and reduce test scatter. The trigger may consist of a local geometric imperfection, pre-bend, notch, reduced section or intentionally unreinforced region. Its geometry, position and orientation shall be specified. Reinforced and unreinforced components shall use equivalent triggers unless the reinforcement itself forms part of the triggering concept.

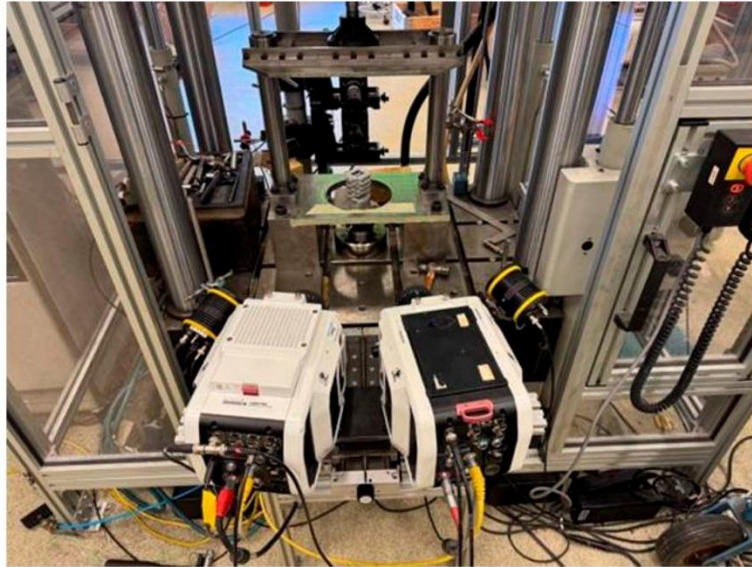


Figure 16 — High-speed axial compression test setup with stereo high-speed cameras

A nominal impact velocity of approximately 10 m/s may be used as an initial high-speed condition for comparative crash-box assessment. The actual velocity shall be measured close to first contact for every test and shall be reported instead of relying solely on the machine setting. Tests outside the predefined velocity tolerance shall be identified and assessed separately. The target crush displacement shall be sufficient to capture progressive folding without reaching fixture interference or complete densification unrelated to the intended assessment. Force shall be measured using a calibrated load cell or instrumented impactor with adequate capacity, resolution and frequency response. Crush displacement may be obtained from the actuator or impactor position, high-speed imaging, laser measurement or another synchronised method. The measurement shall represent component deformation rather than unrelated compliance of the machine or fixture. Where fixture compliance is not negligible, it shall be corrected or reported as a limitation. Force and displacement shall be acquired using a common time base at a sampling frequency sufficient to resolve first contact, the initial force peak, formation of successive folds and abrupt load reductions. The acquisition frequency, zero correction, synchronisation and filtering procedure shall be reported. Raw signals shall be retained. Filtering shall not remove physically relevant peaks or alter the correspondence between force, displacement and recorded images.

High-speed imaging shall be used to document fold initiation, deformation progression, cracking and interface separation. A frame rate of approximately 10 000 frames/s may be used as an initial value for testing near 10 m/s, provided that sufficient image resolution, illumination and exposure are maintained. At least one camera shall show the complete deforming region. Additional views should be used where damage can occur on several reinforced faces. Stereo imaging and three-dimensional digital image correlation may be used to determine full-field displacements and strains. Where DIC is applied, the camera calibration, field of view, spatial resolution, frame rate, subset or facet size, step size, strain filtering and correlation-validity criteria shall be reported. Full-field strain measurements close to severe folds or self-contact shall be interpreted cautiously because curvature, loss of visibility and pattern damage can invalidate the correlation.

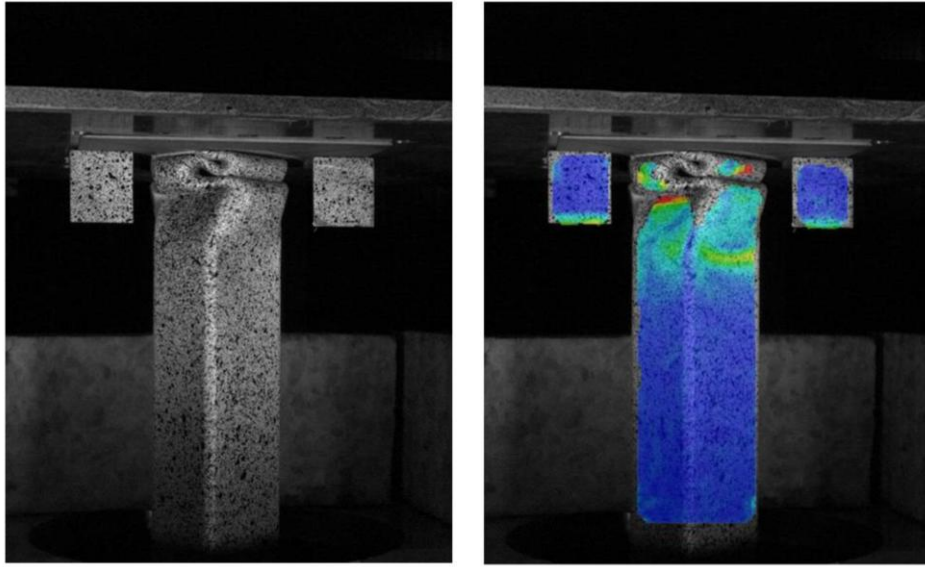


Figure 17 — High-speed imaging of a crash box without reinforcement — Raw image (left) and with strain over field overlay (right)

The axial force-displacement curve shall be reported for every individual component. Absorbed energy, E , up to a specified crush displacement, δ_i , shall be calculated as defined in equation 1. The initial peak force shall be determined using a declared filtering procedure. The mean crush force over a displacement interval from δ_1 to δ_2 may be calculated as:

$$F_{mean} = \frac{E(\delta_2) - E(\delta_1)}{\delta_2 - \delta_1} \quad (8)$$

The selected interval shall be reported and applied consistently. Mass-specific energy absorption may also be calculated, but the mass basis shall be stated explicitly and shall distinguish between total component mass, substrate mass and deposited reinforcement mass. The deformation sequence shall be assessed from the high-speed images. The analysis shall identify the position and timing of the first fold, number and sequence of subsequent folds, asymmetric deformation, global bending, reinforcement cracking and interface separation. Fold development shall be related to the reinforcement layout, gaps, intersections and intended trigger regions. A configuration shall not be considered favourable solely because it increases absorbed energy if it also produces excessive peak force, unstable deformation or premature failure.

Post-test examination shall be performed before the component is sectioned or otherwise modified. Photographs shall document all reinforced faces, component ends, folds and visible damage (Figure 18). Cracks and separated regions shall be mapped to the original reinforcement path. Damage shall be classified as substrate cracking, deposited-material cracking, reinforcement-root cracking, interface separation, lack-of-fusion-related failure, fold-contact damage, end-constraint damage or mixed failure.

Where interface separation occurs, its length and location should be measured. Metallography or fractography should be used where visual examination cannot determine whether failure propagated through the deposited material, along the fusion boundary, through a lack-of-fusion region or within the heat-affected substrate. A three-dimensional scan may be used to document the final component geometry and compare the measured deformation with numerical predictions.



Figure 18 — Crushed crash boxes with straight ribbed reinforcements without cracks and clear folds

Numerical models used to reproduce the test shall represent the measured component geometry, material conditions, reinforcement layout, boundary conditions and actual impact velocity. Substrate and deposited reinforcement behaviour shall be represented separately where appropriate, and interface separation or reinforcement failure shall be included when observed experimentally. Validation shall compare the force-displacement response, peak force, mean crush force, cumulative energy, fold initiation, fold sequence, final deformation and failure location. Agreement in final shape alone shall not be considered sufficient model validation.

A test shall be identified as invalid when the response is materially affected by velocity outside the declared tolerance, component misalignment, fixture displacement, premature loss of support, sensor saturation, incomplete acquisition, loss of synchronisation or failure outside the intended crush region. Invalid results shall remain traceable together with the technical reason for exclusion.

The test report shall include the component and reinforcement materials, manufacturing history, measured geometry, wall thickness, reinforcement layout, deposited mass, total mass, trigger configuration, fixture arrangement, nominal and measured impact velocity, target displacement, instrumentation, sampling frequency, filtering and imaging conditions. For each component, the report shall provide the individual force-displacement and cumulative-energy curves, peak and mean force, absorbed energy over defined intervals, number and location of folds, crack and delamination locations, final shape and damage classification.

An increase in absorbed energy shall not by itself demonstrate improved crash performance. Peak force, intrusion, mean crush force, deformation stability, added mass, cracking, interface integrity and repeatability shall also be considered. Conclusions shall remain specific to the tested material, component geometry, reinforcement layout, manufacturing route, boundary conditions and impact velocity.

11 Reporting, traceability and decision criteria

Manufacturing, inspection, testing and modelling activities shall be documented to ensure traceability and support the qualification decision. Every coupon, component, material batch, process file, test and model version shall have a unique identifier. Original data and images shall be retained, and any processing, correction or exclusion shall be documented. The manufacturing record shall include substrate and powder identification, material condition, relevant equipment and software, atmosphere, process parameters, toolpath revision, fixture, surface preparation, post-processing, in-process deviations, inspection results and final disposition.

The test report shall define the objective, specimen or component geometry, manufacturing history, reference and reinforced conditions, test configuration, instrumentation, loading conditions, data-processing method and validity criteria. Individual results shall be reported together with scatter, uncertainty, damage observations, excluded tests and methodological limitations. Where numerical models are used, calibration and validation data shall be distinguished. The qualification decision shall consider the following areas:

Decision area	Required evidence
Manufacturing feasibility	Repeatable deposition without substrate perforation, process instability or unacceptable distortion
Material quality	Controlled geometry, bonding, dilution, porosity, lack of fusion, cracks and interface continuity
Mechanical function	Specimen- and component-level evidence of the intended response without unacceptable failure
Model reliability	Independent comparison of force, energy, deformation and failure
Transfer to production	Repeated builds, representative equipment, monitoring, inspection and process-control evidence

A nonconformance shall be documented and assigned a disposition: acceptance with technical justification, qualified repair, rework, additional investigation or rejection. The final qualification shall define the accepted material, equipment, geometry and parameter range, required controls and conditions requiring requalification.

12 Limitations, transferability and safety

Transfer to another alloy, temper, powder specification, machine, nozzle, substrate thickness, fixture or component geometry requires documented confirmation. A process window developed on a thick plate or simple track shall not be assumed valid for thin components, multilayer structures, intersections or curved paths. Mechanical results remain specific to the tested geometry, loading condition, rate and interface. Small datasets may support comparative assessment but do not establish statistical design allowables or reliability levels. Numerical predictions shall remain within their validated domain.

This document does not replace laboratory procedures or a formal risk assessment. Aluminium powder, lasers, inert gases, hot surfaces, moving machinery, high-speed impact and mechanical loads require equipment-specific safeguards, trained personnel and authorisation by the responsible organisation.

Bibliography

- [1] DU BOIS, Paul, et al. Vehicle crashworthiness and occupant protection. *Automotive Applications Committee, American Iron and Steel Institute, Southfield, Michigan*, 2004.
- [2] BRUZZO, Francesco, et al. Characterization and simulation of AlSi10Mg reinforcement structures by direct energy deposition by means of laser beam and powder. *Journal of Laser Applications*, 2024, vol. 36, no 4.
- [3] FRÓMETA, David, et al. On the correlation between fracture toughness and crash resistance of advanced high strength steels. *Engineering Fracture Mechanics*, 2019, vol. 205, p. 319-332.
- [4] PARAREDA, Sergi, et al. A damage-based uniaxial fatigue life prediction method for metallic materials. *Materials & design*, 2023, vol. 231, p. 112056.