

Directed-Energy Deposition and Wire-Arc Additive Manufacturing: Repair, Large-Scale Deposition, Thermal History, Machining and Qualification

Energy–Feed Coupling, Substrate Genealogy and Complete-Cell Evidence

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Statement of Significance

Directed-energy deposition can add metal to a substrate, build a large near-net preform or restore selected geometry on an existing component. Those capabilities arise from local fusion during feedstock delivery, but they do not make DED a single process or make the as-deposited object a finished part. Powder-fed laser DED, wire-fed laser DED and arc-based wire DED/WAAM differ in feed transport, directional sensitivity, shielding, bead scale, thermal input, material utilisation, defect mechanisms and cell architecture. In every route, the substrate participates in heat flow and becomes part of the product. Repair adds prior service, damage, material removal, groove geometry and return-to-service authority to that state. This review treats energy source, feedstock, nozzle or torch, melt pool, dilution, path, interpass condition, post-treatment, machining and inspection as one controlled production chain. It bounds high deposition rate, large scale, repair, monitoring and multi-material claims to the tested process–material–geometry state and replaces printer-centred comparisons with accepted-part evidence.

Abstract

Directed-energy deposition (DED) uses concentrated thermal energy to melt feedstock as it is delivered to a substrate or existing component. The category includes powder-fed and wire-fed laser-beam systems and arc-based wire systems commonly called wire-arc additive manufacturing (WAAM); these architectures cannot share an assumed process window. Powder flow or wire-feed speed, energy delivery, travel, standoff, shielding, bead overlap, substrate heat flow and interpass history jointly determine catchment, melt-pool behaviour, dilution, geometry and defects. A nominal power, current or energy-per-length surrogate does not describe those interactions. Repeated thermal cycles create location- and direction-dependent microstructures, residual stress and distortion, while repair geometry and prior material state can invalidate a flat-coupon window. The as-deposited object is usually near-net: heat treatment, machining allowance, surface creation, inspection and final disposition remain part of the route. Functionally graded or multi-material deposition additionally requires composition, dilution, phase and interface control. In-process optical, thermal, electrical or geometric signals can support control only after their correlation, registration and coverage are validated. This qualitative engineering review maps the complete chain from substrate/feedstock release through deposition, interpass control, post-processing, safety and qualification. It supplies no transferable parameter, heat-treatment, machining or acceptance recipe.

Keywords: *directed energy deposition; DED-LB; DED-Arc; wire-arc additive manufacturing; WAAM; repair; dilution; thermal history; machining allowance; qualification*

1. Purpose, scope and terminology

ISO/ASTM 52900 defines directed energy deposition as an additive-manufacturing category in which focused thermal energy fuses materials as they are deposited [1]. The definition establishes process identity, not equivalence among energy sources or feed systems. ER-150 therefore distinguishes powder-fed laser-beam DED, wire-fed laser-beam DED and arc-based wire DED/WAAM. Electron-beam wire deposition is acknowledged only as a separate boundary whose vacuum environment, beam interaction and cell constraints require its own evidence.

The scope begins before the first bead. It includes requirements, substrate or repair-component receipt, damage assessment and material removal where relevant, powder or wire release, gas and shielding state, surface preparation, fixturing, calibration, path and parameter definition, deposition, interpass control, monitoring, heat treatment, separation or substrate removal, machining, surface conditioning, cleaning, inspection, test, disposition, production economics, safety and change control. ASTM F3187 provides DED-specific guidance and ASTM F3413 provides DED design guidance, but neither supplies a universal operating or acceptance window [3,4].

The term `DED-LB` is used when a laser beam is the energy source. `Powder-fed laser DED` specifies powder entrained in carrier gas and delivered through a coaxial or lateral nozzle. `Wire-fed laser DED` specifies wire delivered into a laser-generated melt pool. `DED-Arc` specifies an electric arc and wire feed; `WAAM` is retained where used by the cited study or industrial community. Gas-metal-arc, gas-tungsten-arc and plasma-arc implementations are not assumed identical. Operator qualification is likewise separated in ISO/ASTM 52926-4 for DED-LB and ISO/ASTM 52926-5 for DED-Arc [5,6].

DED directly fuses metal. It does not create the binder-held green state of binder jetting, bound-metal extrusion or lithography-based metal manufacturing. Those routes belong to ER-147, ER-148 and ER-149. Laser- and electron-beam powder-bed fusion belong to ER-145 and ER-146. The direct/indirect distinction is important, but it does not erase downstream states. `As-deposited`,

`stress-relieved`, `heat-treated`, `machined`, `surface-finished`, `inspected` and `delivered` remain different material and geometry conditions.

The corpus-level technology-selection gate is inherited from ER-139, and the direct-versus-indirect route boundary from ER-049 [15,36]. ER-150 owns the DED/WAAM industrial question that follows that gate: whether a declared substrate–feedstock–energy–delivery architecture can establish a qualified local fusion, dilution, thermal, machining and inspection chain for the actual component.

Repair is included only when the complete component route is declared. Depositing a sound wall on new flat plate is useful process-development evidence, but it is not qualification for a serviced blade, shaft, die or pressure boundary. The original component brings chemistry, prior processing, heat treatment, residual stress, service exposure, damage, contamination, geometry and ownership of the return-to-service decision. Recent studies on complex Ti-6Al-4V and IN718 grooves show why geometry-specific transfer matters [23,24].

Large-scale deposition is also bounded. Wire/arc systems can create near-net preforms beyond the convenient envelope of many powder-bed systems, but large geometry increases heat accumulation, restraint, access, metrology, handling and machining obligations. `Large`, `high deposition rate`, `repair`, `low waste` and `near-net` are therefore conditional descriptions, never stand-alone acceptance claims.

This review provides no powder distribution, wire diameter, chemistry tolerance, surface-preparation limit, laser power, current, voltage, travel speed, feed rate, standoff, gas flow, bead overlap, interpass temperature, dwell, path sequence, heat treatment, machining allowance, NDT setting or acceptance limit. Each belongs to a declared material–energy–feed–cell–geometry–state–intended-use combination.

2. Process identity and the state-resolved production chain

The DED production chain joins two incoming states: feedstock and substrate. Powder or wire must arrive with controlled identity and history. The substrate can be new stock, a purpose-made preform or an existing component after defect removal. Its surface becomes a moving heat sink and then an interface inside the product. Energy and feed converge at the melt pool, where part of the substrate and prior bead can remelt. Solidification creates a deposit whose chemistry, geometry and microstructure vary through the build and heat-affected region.

Table 1. State-resolved DED and WAAM production chain

Stage	Controlled state	Principal evidence	Invalid shortcut
Requirements and route definition	Delivered geometry, material, service boundary, critical regions, process family and post-process	Drawing/specification, risk analysis and customer/provider agreement	“DED metal part”
Substrate or repair intake	Identity, prior history, damage, removal geometry, cleanliness, heat-sink and restraint state	Genealogy, examination, preparation and released interface	“Same alloy substrate”
Feedstock and utilities	Powder/wire lot, surface and storage; gas, carrier, shielding and consumables	Certificates plus verified identity, specified tests and lifecycle record	“Correct powder/wire”
Cell and path release	Energy/feed delivery, motion, nozzle/torch, standoff, calibration, software, fixture and path	Registered machine state and dry-run or reference evidence	“Correct power and speed”
Deposition and interpass control	Melt-pool/bead state, dilution, overlap, temperature, dwell, shielding and anomalies	Time/position-linked process and geometry evidence	“Stable arc/melt-pool”
As-deposited release	Near-net geometry, allowance, surface, fusion, pores/cracks, microstructure and residual state	State-specific inspection, witnesses and hold point	“Build completed”
Post-process	Heat treatment, rolling/peening where specified, separation, machining, finishing and cleaning	Qualified sequence with state-linked records	“Stress relieved and machined”
Delivered acceptance	Final geometry, surface, chemistry, interfaces, defects and properties	Part-linked tests, uncertainty, genealogy and disposition	“Coupon passed”

The chain prevents four category errors. First, maximum feed rate is not accepted deposition rate. Powder can miss the melt pool; wire can produce unstable transfer; material can later become machining chip or scrap. Second, a stable bead is not a qualified component. Fusion, composition, microstructure and residual stress may be unacceptable beneath an apparently regular surface. Third, in-process monitoring is evidence about a registered process event, not a universal substitute for inspection. Fourth, the substrate is not disposable build furniture when it remains in the product.

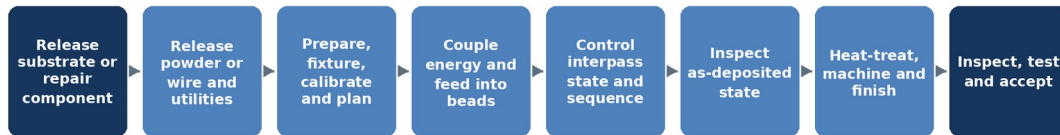


Figure 1. State-resolved route for deposition, repair and acceptance.

Traceability crosses several spatial frames. Feedstock lot and storage history link to feeder or wire package. Machine coordinates link to path, pose, standoff and process signals. Part coordinates link to substrate, deposit, interface, repair groove and critical regions. Time links to interpass delay, temperature and monitoring. Post-process coordinates link removed stock and final inspection back to the deposited volume. ISO/ASTM 52951 and 52953 provide data-package and monitoring-registration architecture, but do not decide what proves conformance [12,13].

For purchased parts, ISO/ASTM 52901 requires customer/provider communication about feedstock, process, final characteristics, inspection, acceptance and documentation [9]. A requirement for ‘DED IN718 repair’ remains incomplete without the incoming component state, defect-removal boundary, allowed dilution or heat-affected region, delivered heat treatment, geometry, surface, inspection coverage and return-to-service authority. ISO/ASTM 52920 places that work inside a controlled industrial site with qualified personnel and equipment [2].

The aerospace wire/arc standard ISO/ASTM 52943-2 demonstrates that wire/arc production requires process-characteristic and performance controls [7]. Its existence does not make every WAAM cell aerospace-qualified. The applicable sector, design authority and regulatory scheme still govern qualification and release.

3. Feedstock, substrate and repair-component eligibility

Powder-fed DED begins with powder identity, chemistry, morphology, size distribution, surface condition, moisture or adsorbates, contaminants and flow behaviour. ISO/ASTM 52907 structures powder characterisation and ISO/ASTM 52928 structures powder lifecycle management [16,17]. These controls remain necessary but insufficient. Carrier-gas transport, feeder response, line geometry, electrostatic or moisture effects, nozzle wear and catchment alter what reaches the melt pool. A released bottle is not a released powder stream.

Powder flow is measured at the delivery point or correlated to it over the intended feeder range and duty cycle. Start-up, ramp, stop, low-level operation and refill can differ from steady-state mass flow. Multiple hoppers for alloy development or graded deposition add calibration of each stream and the mixed composition. Recovered overspray can be reused only under a defined identity, contamination and history rule. Powder lost outside the bead is neither harmless nor automatically recyclable.

Wire simplifies some loose-powder operations but adds its own state. Chemistry, diameter, cast, helix, surface, lubricant or residue, spool history, straightening, drive-roll condition and feed stability affect delivery. Wire-feed speed does not equal accepted mass deposition when transfer, stubbing, droplet behaviour, start/stop loss or bead rejection intervenes. Wire changes reduce powder-handling exposure, but arc fume, hot work, sharp ends, drive mechanisms and large moving equipment remain.

Shielding and carrier gases are process inputs. Gas identity, purity, moisture/oxygen control, flow architecture, local enclosure, cross-draft and nozzle or trailing-shield geometry affect oxidation and bead integrity. Choi et al. linked local shielding to defects and fatigue behaviour in their Ti-6Al-4V laser-DED repair study [25]. That result does not create a universal gas-flow setting; it establishes shielding as a part- and path-dependent qualification variable.

The substrate is simultaneously an incoming material, a geometric datum, a fixture interface, a heat sink and a metallurgical participant. New substrates require identity, chemistry, heat treatment, thickness, flatness or form, surface preparation and cleanliness. Thin or low-stiffness substrates can distort early; thick or actively cooled substrates can extract heat and change penetration. Surface oxide, lubricant, machining fluid, paint, scale or embedded abrasive can create porosity, inclusions or chemistry changes. Preparation is followed by protected storage and a maximum qualified interval before deposition.

Repair intake adds failure analysis. The defect or worn volume must be located, bounded and removed to an inspectable geometry. Crack tips, oxides, service deposits or altered material cannot be buried beneath new metal. Groove angle, depth, root radius, wall inclination and access change heat flow, melt-pool visibility, nozzle or wire orientation and shielding. Sutherland et al. found that settings developed for simpler geometry did not transfer cleanly into a complex inclined Ti-6Al-4V groove, with underbuilding and thermal accumulation among the reported challenges [23]. The transferable rule is representative geometry and state, not their particular parameters.

Material compatibility is evaluated across the interface and heat-affected zone. Nominally matching alloy names can hide product-form, heat-treatment or composition differences. Dissimilar repair or cladding intentionally creates dilution. The deposited chemistry near the first layers can differ from the incoming feedstock, and repeated remelting can extend that transition. Interface evidence therefore includes local composition, fusion, phases, hardness or other relevant response, not only bulk deposit analysis.

Incoming acceptance defines a stop decision. Unresolved genealogy, service damage, inaccessible crack removal, contamination, excessive section loss, unqualified dissimilar combination or inability to inspect a critical region holds or rejects the component before deposition. Additive capability does not override design authority or make every damaged part repairable.

4. Energy–feed coupling, melt pool, bead geometry and dilution

DED performance emerges where energy, feedstock and motion interact. For laser DED, relevant variables include delivered power distribution, spot size and focus, incidence, travel, powder or wire delivery, standoff, shielding and material absorptivity. For DED-Arc, current, voltage, polarity or waveform, electrode/wire relation, travel, torch angle, contact-tip distance, shielding and transfer mode enter the state. Material thermophysical properties, substrate temperature and previous beads complete the boundary conditions.

Scalar surrogates such as power divided by speed or electrical heat input per length can support comparison within a controlled experiment. They do not preserve spot or arc geometry, absorptivity, efficiency, feed rate, bead size, remelting or three-dimensional heat loss. Xian et al. demonstrated heat-input-linked microstructure and mechanical changes in a defined Ti-6Al-4V WAAM study [31]. Their evidence justifies tracking coupled thermal input; it does not provide a universal threshold.

The melt pool must accept incoming material and wet/fuse the substrate or prior layer while avoiding excessive penetration, vaporisation, spatter or collapse. Too little local energy relative to feed and heat loss can leave unmelted powder, wire stubbing, irregular transfer or lack of fusion. Too much can enlarge the pool, deepen dilution, increase evaporation, destabilise the surface, widen the heat-affected zone and intensify distortion. The acceptable window depends on bead function: first-layer fusion, wall building, infill, contour, repair root and graded transition can require different control.

Bead geometry includes width, height, penetration, toe shape, wetting, reinforcement and longitudinal regularity. It controls overlap and layer increment. A high bead may increase build rate and roughness or create weak overlap valleys; a wide pool can improve lateral fusion while erasing features and increasing heat input. Multi-bead layers require overlap that fuses neighbours without accumulating excessive crowns or depressions. The planned path must reflect the measured bead under the relevant local thermal condition.

‘Dilution’ is not accepted as one unqualified percentage. A geometric dilution measure may be declared on a transverse section, for example melted-substrate area below the original surface divided by total fused area under a specified contour rule. A compositional dilution estimate may instead infer substrate contribution by marker-element mass balance from declared feedstock/substrate compositions. These measures are not equivalent: section geometry is local and plane-dependent, while composition can be altered by evaporation, mixing, segregation or analytical resolution. Pool asymmetry makes a single transverse area especially location-sensitive. Matched-alloy deposition can show substantial remelting while providing no usable compositional contrast; in that case the geometric route, with a declared sectioning plan and uncertainty, is the only available dilution evidence.

Zero dilution would generally mean no metallurgical fusion; excessive dilution can move composition outside the intended range, deepen the heat-affected zone or consume a thin repair wall. The section plan therefore declares section orientation, location, contour rule, numerator/denominator, start/steady/corner/slope/end coverage and measurement uncertainty. Composition maps declare sampling volume, calibration, spatial resolution, evaporation-sensitive elements and the feed/substrate end members used in any mixing calculation. A result is accepted only for the metric actually measured. The required control region is also explicit: the functional surface, the whole deposited volume, the interface/heat-affected zone, or more than one of these according to service function.

Powder catchment is conditional. A coaxial nozzle can deliver powder around the beam and reduce the directional limitation of a lateral jet, yet focus position, cone convergence, carrier flow, particle inertia, plume interaction, standoff and surface angle affect capture. Material that misses the pool can contaminate surfaces or equipment and alters mass efficiency. A lateral nozzle makes travel direction and surface orientation more explicit. Neither arrangement is qualified by a schematic alone.

Wire must enter the pool at a controlled position and angle. Leading, trailing or side feed changes preheating, wetting and accessibility. Wire touching unmelted solid can deflect or stub; wire entering an oversized pool can produce irregular transfer. Wire curvature, robot pose and path reversal can shift the entry point. A wire-fed laser process can have a smaller or differently controlled energy field than an arc route, but it still requires geometry-specific alignment evidence.

Start, stop, corner and transition regions deserve separate qualification. Feed and energy have finite response times; robot velocity can change through acceleration and curvature; the substrate becomes hotter; a closed loop returns to its initial region. Ramps, lead-ins, run-off features, dwell or local parameter changes may be justified, but every strategy becomes part of the controlled file. A single steady straight bead cannot represent them.

5. Powder-fed laser DED

Powder-fed laser DED entrains particles in carrier gas and directs them toward a laser-generated melt pool. Coaxial configurations can support multi-axis deposition because the powder stream surrounds or approximates the beam axis. Lateral configurations can be simpler or provide advantageous access, but create a stronger relation between nozzle orientation and travel. NIST describes powder-blown DED as a platform for deposition, repair and composition exploration, while treating measurement and process understanding as active research needs [19].

The powder-delivery chain includes hopper, metering device, carrier gas, lines, splitter where present, nozzle and stand-off space. Pulsation, segregation, line deposition, leaks, humidity, electrostatic charging and feeder-level effects can alter flow. Calibration by feeder command alone is insufficient unless its relation to delivered mass remains verified. Multi-hopper systems require independent calibration and evidence that commanded ratios become deposited composition after different transport and catchment efficiencies.

Nozzle state is a consumable process condition. Powder impingement, heat and spatter can erode or obstruct orifices. A nominally concentric nozzle can become asymmetric. Alignment between powder focus and laser focus can drift after collision or maintenance. Inspection intervals are based on measured stability and risk, with a release check after nozzle change, crash, cleaning or beam-path work.

Standoff and surface pose govern both focus and powder convergence. Deposition on a curved repair or five-axis path changes the local surface normal, gravity relation and nozzle clearance. A path that is reachable by the robot can still be outside the qualified powder-focus or shielding condition. Collision avoidance, cable/hose motion and line-of-sight monitoring constraints are included in path verification.

Powder-fed DED can switch or blend feedstocks more readily than a single-wire system, supporting composition studies and some graded structures. That opportunity brings residual powder in lines, hopper cross-contamination, different transport efficiency, evaporation and dilution. The delivered transition can lag or smear relative to the command. Composition is therefore measured spatially and linked to the feed-change history rather than inferred from commanded hopper fractions.

Monitoring can view relative temperature, material emission, laser reflection, pool geometry or deposition surface. Webster et al. measured parallel wavelength-band signals in powder-blown DED and linked changes to laser coupling phenomena in their controlled experiments [22]. The study supports multi-phenomenon observation; it does not show that one signal or threshold certifies every defect or alloy. Calibration, field of view, emissivity, plume obstruction, saturation and position registration remain.

Powder safety extends beyond filling the hopper. Loading, sampling, spill cleanup, filter service, nozzle cleaning, overspray recovery, housekeeping and machining of deposits can create exposure. NIOSH's evaluation of one metal-powder AM facility shows the value of task-specific measurement and controls, but its findings cannot be copied into another site as proof of compliance [21]. Powder combustibility, reactivity and occupational limits are established for the actual alloy and particle state.

6. Wire-fed laser DED and DED-Arc/WAAM

Wire-fed laser DED and DED-Arc both deliver continuous metallic wire, but their energy and transfer mechanisms differ. In laser wire deposition, the beam creates the pool and preheats or melts the incoming wire according to its position. In DED-Arc, the wire can be an electrode or be fed separately into an arc-generated pool, depending on the architecture. These differences affect electrical circuit, heat distribution, deposition scale, control signals, spatter, shielding and cell safety.

Wire offers high incoming-material capture when delivery is stable because the feed is aimed into the pool rather than dispersed through a powder plume. That does not establish high final yield. Starts, run-off, unstable transfer, support or substrate material, witness pieces, machining stock, removed surfaces, test specimens and rejected components remain in the material balance. Material efficiency is accepted-part mass divided by released input across the defined cell boundary.

Arc systems can support high mass deposition and large preforms, but deposition rate competes with bead size, heat accumulation, surface waviness, path access and machining. Increasing wire feed can require increased energy and pool volume. Larger beads reduce the number of layers while decreasing geometric resolution and increasing stock. The useful metric is accepted geometry per complete-cell time, including interpass delay and machining, not wire-feed speed alone.

WAAM toolpaths commonly build walls or preforms from overlapping beads. Local geometry evolves as heat accumulates and the substrate's heat-sink effect weakens. Layer height can drift, changing contact-tip distance, arc length, wire position and robotic accuracy. Closed-loop height correction may improve consistency, but its sensor, control authority and response to local anomalies require qualification. A corrected height does not prove fusion or microstructure.

Aluminium routes illustrate coupled shielding and pore risk. Ujjwal et al. investigated heat-input and inert-gas-flow control for porosity and surface defects in a specific WAAM aluminium alloy [32]. Their results reinforce control of oxide, hydrogen-related and shielding-sensitive mechanisms in that experiment. They are not transferable gas-flow or energy settings for other alloys, torch geometries or rooms.

Ti-6Al-4V illustrates thermal and atmospheric sensitivity. Vázquez et al. linked interpass cooling conditions to microstructure and tensile properties in their WAAM specimens [30], while Xian et al. examined heat input [31]. These studies show that layer scheduling and heat input belong to the material state. They do not support a universal cooling time, temperature or property equivalence.

Arc cells combine hot work, electrical energy, radiation, fume, gas, wire drives and robot or gantry motion. Large deposited objects retain heat and can move or distort after restraint changes. Access control, extraction, gas/asphyxiation assessment, electrical protection, fire prevention, collision zones, lifting and maintenance are designed around the actual cell. Automation changes who is exposed and when; it does not remove the hazards.

7. Toolpath, interpass state and thermal accumulation

Each new bead reheats the substrate, neighbouring beads and earlier layers. The thermal history therefore depends on sequence, path length, direction, layer geometry, dwell, interpass condition, fixture, preheat, active cooling and the evolving part. Identical energy/feed commands can produce different pools at the cold start, mid-build and thermally saturated region. Process qualification maps those regimes rather than applying one steady-state label.

Interpass temperature is a spatial and temporal quantity. A single point on the visible surface may not represent the pool start, repair root, thick junction or constrained substrate. The measurement method, emissivity assumption, field of view, location, delay and decision rule must be declared. Contact measurement can disturb the route; radiometry can be sensitive to surface and viewing. A temperature threshold without method and position is ambiguous.

Path strategy distributes heat and shrinkage. Unidirectional raster, alternating direction, island, spiral, symmetric and segmented sequences create different start/stop populations and restraint. For a wall, reversing travel can change wire/nozzle orientation relative to the pool. For a repair groove, deeper layers have different access and heat loss than fill layers near the surface. Simulation can inform sequence, but its material data, heat-source representation, boundary conditions and validation domain must be documented.

Interpass dwell can lower temperature while reducing equipment utilisation. Active cooling can change gradients or introduce contamination/condensation risks. Substrate preheat can reduce early gradients while extending total hot exposure and changing oxidation or phase evolution. Interpass mechanical treatments such as rolling can modify geometry, strain and residual stress. Martina et al. demonstrated microstructural effects of interpass rolling in a defined Ti-6Al-4V WAAM route [27]; the treatment is not a generic corrective action.

Repeated thermal cycles create bands or region-specific phase evolution. Ho et al. investigated the origin of microstructural banding in high-deposition-rate Ti-6Al-4V wire-arc manufacture and connected it to cyclic thermal history [29]. A visually regular band pattern is not necessarily a defect by itself, but it shows why location and thermal history must accompany material-property evidence.

Build height weakens the substrate heat sink and changes compliance. Long walls or large shells can accumulate temperature, bow, twist or move relative to the programmed path. Corners and intersections retain heat differently from isolated straight sections. Layer-height or bead-width control that ignores underlying motion can chase geometry without resolving root thermal imbalance.

The controlled record links each deposited volume to path segment, pose, feed/energy commands, measured interpass condition, monitoring and deviations. Data volume is managed by preserving sufficient raw or losslessly interpretable evidence for critical regions and validated summaries elsewhere. ISO/ASTM 52953 supports registered process-monitoring data [12], but acceptance logic remains application-specific.

8. Defects, residual stress and distortion

DED defects arise from different physical routes and require different controls. Lack of fusion can occur between deposit and substrate, adjacent beads or layers when energy, overlap, surface, feed or pose is inadequate. Pores can arise from gas, contamination, unstable transfer, entrained powder or keyhole/vapour-depression behaviour where relevant. Oxides or inclusions can enter through feedstock, surface contamination, insufficient shielding or spatter. Cracks can be solidification-, liquation-, hydrogen-, strain-age- or stress-related depending on alloy and thermal state.

Geometric discontinuities include underfill, overbuild, humping, waviness, collapsed walls, bead wandering and start/stop craters. Powder processes can leave partially melted particles or overspray on surfaces. Wire processes can stub, buckle or transfer irregular droplets. A surface scan can identify some shape anomalies while missing subsurface fusion or composition. A density value can average away a critical interface defect.

Failure-mode mapping connects cause, observability and consequence. Energy/feed imbalance, standoff drift, nozzle obstruction, wire misalignment, loss of shielding, temperature excursion, fixture motion and contaminated preparation generate different signatures. Monitoring is selected for a hypothesis and validated detection capability, not installed as a generic quality label. NIST IR 8538 describes both opportunities and remaining correlation/NDE gaps for metal AM [20].

Residual stress develops as hot deposited material contracts against cooler and restrained material. Magnitude and distribution depend on geometry, sequence, heat input, dwell, substrate and post-treatment. Distortion is the mechanical response of the evolving structure and fixture. Releasing clamps or separating a part can reveal motion that was hidden during deposition. An in-envelope scan before release is therefore not the final geometry state.

Interpass rolling can change residual stress as well as microstructure. Martina et al. compared as-deposited and rolled Ti-6Al-4V wire/arc components and reported treatment-dependent residual-stress behaviour [28]. The study provides evidence for that material, geometry and rolling route; it does not allow rolling to be assumed beneficial or harmless for every alloy and feature.

Repair adds stress concentration and an existing material state. Groove roots, thin remaining walls and stiffness transitions can concentrate thermal and mechanical effects. Wang et al. studied IN718 repair under trapezoidal-groove constraints and documented microstructure and property evolution [24]. Such evidence supports geometry-resolved repair qualification, not a generic IN718 recipe.

Mitigation can involve sequence, lower or redistributed heat input, preheat, interpass control, fixture design, local or global stress relief, rolling/peening or stock allowance. Each action can trade one risk for another. Strong restraint can reduce visible distortion during deposition while raising locked-in stress; long dwell can reduce interpass temperature while altering throughput and thermal cycling; heat treatment can reduce stress while changing phase state or dimensions.

The as-deposited hold point records geometry relative to datum, fixture condition, visible surface, relevant NDT, witness/coupon results, monitoring exceptions and safe authority to release or post-process. It does not approve the delivered part. Hidden defect risk, machining exposure, heat-treatment response and final dimensions remain open.

9. Microstructure, anisotropy and heat treatment

DED solidification begins from a substrate or prior layer and is repeatedly modified by later thermal cycles. Thermal gradient, solidification rate, melt-pool shape, epitaxy, remelting and reheating influence grain morphology, texture, segregation and phase

evolution. These conditions change with height, wall thickness, intersection, repair depth and path. 'DED material' is therefore not a homogeneous material designation.

Columnar growth and directional texture can develop where the thermal gradient remains aligned through layers. Reheating can temper, transform, coarsen or precipitate phases without fully remelting a region. Ti-6Al-4V WAAM studies show how interpass state, heat input and cyclic temperature history affect microstructure and properties [29–31]. The precise outcomes belong to their alloys, cells and specimens; the transferable requirement is location- and state-aware evidence.

Orientation and location are declared in specimen plans. ISO/ASTM 52909 addresses dependence of mechanical properties on orientation and location for metal AM [11]. A vertical tensile bar from a wall centre cannot by itself represent transverse response, starts/stops, interfaces, corners, surfaces, repaired substrate or heat-affected material. Sampling is driven by the failure modes and intended loading.

Surface and machining condition influence fatigue evidence. As-deposited waviness, oxide, adhered powder or arc features can dominate initiation; machining may remove that population while exposing lack of fusion or pores. A machined specimen does not prove an as-deposited surface, and an as-deposited specimen can understate the performance of a fully machined product. State, surface and extraction location accompany every result.

Heat treatment is material-, geometry- and state-specific. Stress relief, solution/ageing, annealing, hot isostatic pressing or other operations can change residual stress, phase balance, grain or precipitate state, pores and dimensions. Aslanis et al. used a two-stage experimental optimisation for DED Ti-6Al-4V processing and post-heat treatment [26]. That work illustrates coupled optimisation; it does not establish a transferable heat-treatment cycle or universal optimum.

Heat treatment cannot be used as a blanket defect eraser. It cannot reliably fuse an unbonded planar interface, remove an oxide inclusion, replace missing material, restore an out-of-tolerance feature or undo contamination. HIP may close some internal pore populations under suitable conditions but can leave chemistry, inclusions, surface-connected defects and geometry unresolved. Post-treatment evidence is compared with the actual failure modes.

Repair properties require separate regions: original substrate remote from repair, heat-affected substrate, fusion/dilution zone, bulk deposit and any transition between deposition regimes. Choi et al. linked local shielding, defects and fatigue in repaired Ti-6Al-4V [25]; Sutherland et al. included tensile and very-high-cycle fatigue evaluation for a complex groove while also reporting unresolved repair difficulties [23]. These studies caution against accepting a repair from bulk deposit strength alone.

Microstructure qualification uses complementary methods: chemistry and phase analysis, optical/electron microscopy, hardness mapping, texture or diffraction where warranted, and mechanical or functional tests tied to service. Sampling and detection limits are recorded. A satisfactory polished cross-section is local evidence, not proof that the entire part shares the same state.

10. Repair, remanufacture, graded and multi-material deposition

Repair begins with authority and eligibility, not deposition. The component owner or design authority defines allowable damage, material removal, repair boundary, number of repair cycles, required properties and return-to-service evidence. Genealogy includes original manufacture and heat treatment where available, service exposure, inspections, damage cause and previous repairs. When that information is missing, uncertainty becomes an explicit hold or risk decision.

Damage removal produces the substrate for deposition. Machining, grinding or another process must remove the affected volume without introducing new cracks, overheating, embedded abrasive or unacceptable geometry. NDT after removal verifies the relevant failure modes to its demonstrated capability. A smooth groove is not proof that the damage mechanism is gone. The groove is measured and registered to the repair path.

The repair geometry evolves from a constrained root to a wider fill and final overbuild. Nozzle or torch access, wire angle, powder catchment, shielding, heat flow and optical monitoring can vary continuously. Sutherland et al.' coaxial-wire laser study on a complex Ti-6Al-4V groove is particularly important because it shows that a planar window and a nominally favourable coaxial architecture did not eliminate transfer problems [23]. A qualified repair family therefore includes representative inclination, depth, curvature, access and thermal mass.

IN718 repair demonstrates another boundary. Wang et al. analysed microstructure and mechanical-property evolution under trapezoidal-groove constraint [24]. Nickel superalloy phase and cracking responses cannot be inferred from Ti-6Al-4V. Material-specific substrate condition, dilution, heat treatment and inspection remain necessary even when machine architecture is shared.

Cladding and remanufacture can add wear-, corrosion- or heat-resistant material rather than matching the substrate. The first layers intentionally mix feed and substrate. Composition can then approach the feedstock through later layers, but pool depth, path and reheating shape that transition. A specification defines whether the functional surface, entire deposited region or interface must meet chemistry and property requirements.

Multi-hopper powder DED can vary composition during a build. Wire systems can change or combine wires through more complex architectures. A commanded fraction is not deposited composition because feeder calibration, transport, residual material in lines, catchment, melting, evaporation and dilution intervene. Spatially resolved composition and phase evidence closes the actual transition.

Functionally graded material is a designed transition, not an absence of interface risk. ISO/ASTM TR 52912 provides design guidance for graded AM [18]. Huang et al. produced an IN718–René41 gradient by blown-powder laser DED and found residual-stress behaviour strongly influenced by process and geometry, alongside columnar microstructure through the gradient [34]. Ghanavati et al.' SS316L–IN718 study identified location-dependent challenges including composition change, lack-of-fusion tendency, heat accumulation and distortion [35]. Neither study implies that arbitrary alloy pairs can be graded safely.

Thermodynamic or kinetic modelling can screen phase formation and cracking risk, while thermal/process models can guide transitions. Their databases, assumptions and validation range are recorded. A continuous nominal composition does not guarantee continuous properties; brittle intermetallics, liquation, segregation, thermal-expansion mismatch or heat-treatment incompatibility can appear at intermediate compositions.

Repair and graded-part acceptance remains component-specific. Evidence includes incoming and removal records, interface and transition maps, representative local properties, final geometry and surface, NDT coverage, post-treatment, deviations and design-authority disposition. A successful material-addition operation is only one step in returning the component to service.

11. Geometry, machining, surface, inspection and monitoring

DED and WAAM usually produce near-net rather than final geometry. Bead width and layer height establish a finite geometric scale; starts, stops, overlaps, heat accumulation and robot accuracy add deviation. As-deposited surfaces can carry waviness, partially fused particles, oxide, spatter or arc features. Critical datums, fits, sealing faces, fatigue surfaces and thin features commonly require machining or another finishing route.

Machining allowance is a controlled geometry field. It must cover deposition deviation, thermal distortion, fixture release, coordinate registration, surface damage and the material needed to establish the specified finish. Too little allowance leaves uncleaned surface or local underfill; too much increases deposition, heat, time, cutting load and material loss. Fuchs et al. developed and experimentally validated a WAAM allowance method incorporating process-chain deviations for Ti-6Al-4V parts [33]. Their method supports evidence-based allowance planning, not one transferable offset.

Datum strategy connects additive and subtractive states. Substrate references can move through deposition and unclamping. In-situ hybrid cells can preserve machine registration while still accumulating thermal deformation and tool/calibration error. External machining adds setup and probing uncertainty. Reference features must survive the route or be recreated by a documented transfer.

Machinability depends on as-deposited microstructure, hardness, residual stress, interrupted surfaces and local composition. Cutting can release stress or reveal defects. The machining process therefore records stock removal sequence, tool and coolant compatibility, dimensional evolution and inspection holds where risk warrants. Chips and removed layers can provide diagnostic evidence but do not substitute for planned sampling.

Inspection is layered. Surface and dimensional metrology address accessible form and roughness. Volumetric methods address selected internal discontinuities subject to geometry, surface and resolution. Penetrant, magnetic, radiographic, ultrasonic, computed-tomographic or other methods are chosen for material, defect orientation, access and probability-of-detection needs. ISO/ASTM TR 52905 provides an AM NDT framework but no method guarantees complete detection [14].

Repair NDT includes substrate, fusion boundary, deposit and finished surface. Machining may improve coupling or remove roughness that masks inspection, while also removing the overbuild that contained witness information. Inspection sequence is therefore planned with machining. A 'no indication' result is bounded by calibration standard, coverage, surface, orientation and acceptance criteria.

In-process monitoring can include melt-pool emission, relative temperature, laser reflection, camera geometry, powder flow, wire feed, electrical waveforms, acoustic signals, interpass temperature, bead profile and robot position. NIST IR 8538 emphasises that signal-to-defect correlation and NDE integration remain active challenges [20]. Webster et al.' parallel laser-DED sensing demonstrates process sensitivity across optical channels, not automatic defect classification [22].

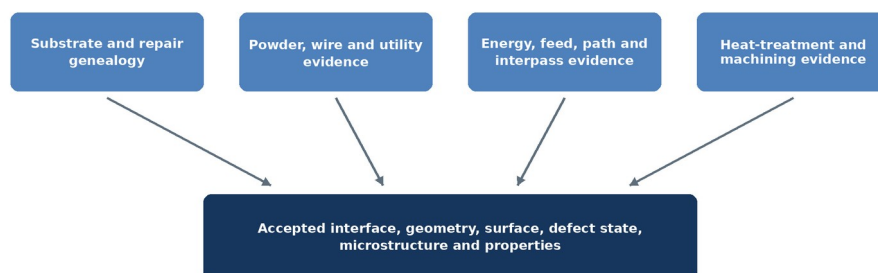


Figure 2. Part-linked DED evidence architecture.

Monitoring systems require calibration, synchronization, coordinate transformation, field-of-view and detection-limit control. Emissivity, plume, arc light, spatter and changing pose can alter signals. Algorithms add model version, training domain, threshold and false-negative controls. A model validated on straight walls does not automatically cover a deep repair groove or graded transition.

Table 2. Conditional opportunities and controlling liabilities in DED and WAAM

Process or application condition	Conditional opportunity	Controlling liability	Evidence required
Powder-fed laser DED	Multi-axis access, local addition and multiple-powder blending	Catchment, plume, powder lifecycle, nozzle state and surface-angle sensitivity	Delivered-flow, focus, pose, dilution and part-state correlation
Wire-fed laser DED	High feedstock capture and controlled local wire delivery	Wire-pool alignment, stubbing, directionality and access	Pose- and geometry-resolved transfer and fusion evidence
DED-Arc/WAAM	Large near-net preforms and potentially high mass deposition	Heat accumulation, bead scale, waviness, fume and machining burden	Complete-cell accepted-part rate and property maps
Component repair	Addition only where material is missing or removed	Prior service, residual damage, constrained groove, interface and authority	Full component genealogy and representative repair qualification
High deposition rate	Shorter ideal additive time for compatible geometry	Larger pool/bead, distortion, dwell, post-process and rejected material	Accepted mass/geometry over complete elapsed cell time
Coaxial powder delivery	Reduced directional dependence relative to a lateral jet	Standoff, focus, pose, catchment and shielding remain	Multi-axis surface/pose validation
In-process monitoring	Earlier anomaly detection and process understanding	Limited correlation, coverage, registration and algorithm domain	Validated signal-state relationship and response plan
Graded or multi-material deposition	Location-specific composition in selected compatible systems	Dilution, lag, phases, cracking and heat-treatment mismatch	Spatial chemistry, phase, interface and property evidence

Final disposition integrates these channels. Normal monitoring cannot clear a failed dimension; a passing CT cannot establish chemistry; bulk tensile strength cannot close a planar interface; an acceptable surface does not prove the repair root. Evidence is combined according to risk, with deviations retained rather than averaged away.

12. Complete-cell productivity, economics, safety and environment

Deposition rate is only one interval in the factory cell. The complete route includes incoming substrate or component inspection, damage removal, powder or wire handling, setup, calibration, programming, dry run, preheat, deposition, interpass waits, cooling, fixture release, heat treatment, transfer, machining, finishing, cleaning, inspection, testing, rework and release. Repair additionally includes logistics, engineering disposition and return-to-service documentation.

Effective component throughput, $T_N = N_{\text{accepted}} / t_{\text{complete-cell}}$, and **effective accepted-mass throughput, $T_m = m_{\text{accepted}} / t_{\text{complete-cell}}$** , have different units and are reported separately. **Material efficiency, $\eta_m = m_{\text{accepted}} / m_{\text{released-input}}$** , is a separate dimensionless ratio. Every metric declares the same process boundary, period, queue state and treatment of overspray, run-off, overbuild, chips, witnesses and rejects.

This metric distinguishes feeder throughput, molten transfer, deposited mass, as-deposited yield and final accepted yield. Powder missing the pool, wire run-off, overbuild, machining chips, witness material and rejected parts are included at the declared boundary. A comparison that counts only deposited mass can favour a route that creates excessive stock or downstream queues.

Large-scale WAAM can reduce the starting billet or forging mass for selected preforms, but machine envelope is not factory capacity. Interpass control, heat-treatment size, lifting, machining envelope, probing, NDT access and floor logistics can become limiting. A deposition cell capable of a large object does not establish that the factory can safely heat-treat, machine, inspect or move it.

Repair economics depend on avoided replacement and restored value, but also on diagnosis, preparation, qualification and failure risk. A high-value component can justify extensive engineering and inspection; a low-value component may not. The valid comparison includes replacement lead time, remaining life, certification and consequence of failure. ‘Less new material’ does not by itself prove lower environmental impact or cost.

Energy and material balances name the boundary. Laser or arc power, chillers, extraction, shielding/carrier gases, preheat, interpass cooling, heat treatment, machining, compressed air, powder recovery and scrap treatment can dominate differently. Near-net production can reduce chip mass relative to machining from solid in a specific case, while deposition inefficiency and overbuild remain. Environmental claims require measured accepted yield and actual utilities.

Safety is process- and task-specific. Laser cells require beam containment, access control, reflected-beam assessment, fume and powder controls, interlocks and maintenance procedures. Arc cells add intense optical radiation, electrical energy, hot-work fire risk, fume and spatter. Both can use robots or gantries with crush/collision zones and gases that can displace oxygen. Large parts and fixtures create lifting, stored-energy and long cooldown hazards.

Powder-fed routes require alloy-specific control for loading, sampling, spills, housekeeping, filters, overspray and maintenance. The fine fraction accumulated in ductwork, filters or collectors is a distinct hazard state rather than ordinary virgin feedstock: it can be finer and higher in specific surface and can include oxidised particles, condensate or fume products of changed composition. Its identification, segregation, transfer, storage, reuse eligibility and disposal require a separate hazard determination for the actual alloy and collection state. NIOSH's facility investigation provides an example of task-resolved metal exposure evaluation, not a universal exposure result [21]. Wire-fed routes reduce routine loose-powder handling but do not remove fume, metal contamination, machining dust or hot-work risk. ISO/ASTM 52931 structures metallic-material environmental, health and safety principles across the chain [8].

Operator qualification is architecture-specific as reflected by separate DED-LB and DED-Arc standards [5,6]. Competence also covers preparation, inspection, powder or wire handling, programming, post-process and emergency response as assigned. Automation transfers tasks; it does not eliminate responsibility.

Local law, design authority, occupational limits, fire codes, pressure or aerospace regulation and environmental permits govern actual operation. This review supplies no universal PPE, gas-flow, ventilation, interlock, exposure or disposal prescription.

13. Qualification architecture and selection gate

Qualification begins at the ER-139 selection gate and uses the ER-049 direct-process boundary [15,36]. It then closes every material state. ISO/ASTM 52920 provides the production-site framework [2]; ASTM F3187 and F3413 provide DED process/design guidance [3,4]; ISO/ASTM 52901 structures customer/provider exchange [9]; and ISO/ASTM 52927 and 52909 structure characteristic, orientation and location evidence [10,11]. Data and monitoring records follow ISO/ASTM 52951 and 52953 [12,13]. None of these documents supplies a universal DED parameter set.

Table 3. DED and WAAM factory qualification and selection gate

Gate	Minimum evidence	Fail or hold condition
Intended delivered state	Drawing/specification, service boundary, critical regions, material, surface, defects, properties and post-process	State, authority or critical failure modes undefined
Substrate/repair eligibility	Genealogy, prior state/service, damage removal, geometry, cleanliness, interface and inspectability	Residual damage, contamination, identity or return-to-service route unresolved
Feedstock and utilities	Powder/wire identity and lifecycle, delivery calibration, gas and consumable controls	Nominal alloy or feeder command used alone
Cell and path release	Energy/feed systems, nozzle/torch, motion, standoff, fixture, calibration, software and accessibility	Relevant drift, collision/access risk or coordinate transfer uncontrolled
Deposition/interpass control	Bead/fusion, declared geometric and/or compositional dilution metric, section/map plan, uncertainty, functional/whole-deposit/interface region, overlap, shielding, thermal state, path and registered anomalies	Undefined dilution percentage, unmatched metrics, straight steady bead or scalar heat input used as sole evidence
As-deposited release	Allowance geometry, surface, fusion/defect evidence, microstructure witnesses and fixture-release plan	Build completion or density used as acceptance
Post-process	Heat treatment, rolling/peening if used, separation, machining, finishing, cleaning and intermediate holds	Generic post-process assumed to repair unknown defects
Delivered part and inspection	Final dimensions, surface, interfaces, chemistry, NDT, properties, uncertainty and disposition	Coupon, monitoring or one NDT method used alone
Factory, productivity and safety	Complete-cell capacity/yield, qualified personnel, task controls, utilities, lifting and legal requirements	Downstream bottleneck or uncontrolled exposure/large-part handling
Change and transfer	Equivalence/requalification for substrate, feedstock, gas, cell, path, software, post-process and inspection	“Same alloy/power/arc/robot” used as equivalence

The route is selected when the geometry can be reached with a controlled energy/feed/shielding condition; the substrate and interface can be released and inspected; representative deposition achieves required fusion, composition, geometry and material state; post-processing can establish the final surface and dimensions; the inspection plan covers critical defects; and complete-cell capacity, cost and safety meet the use case.

It is held or rejected when repair damage cannot be removed or verified; the nozzle, torch or wire cannot maintain pose and shielding; heat accumulation or distortion cannot be controlled; machining allowance cannot guarantee clean-up; interface, transition or internal regions cannot be inspected; material or heat-treatment compatibility is unresolved; or the site cannot safely contain, move or post-process the component.

Change control is intentionally broad. Substrate supplier/product form/heat treatment, prior service, groove or preparation; powder or wire lot and form; gas or consumable; feeder, line, nozzle, wire drive, beam, arc source, torch, motion system, fixture or sensor; calibration, software, path, parameter schedule, interpass method; heat treatment, rolling/peening, machining, surface process, inspection method or acceptance logic can change the delivered state. Nominally identical machines do not prove equivalence.

Equivalence is tiered. A change that can introduce a new failure mode, alter an unrepresented substrate, feedstock, energy-delivery, path, dilution, interpass, post-process or delivered-part state, or affect acceptance requires full requalification of the affected chain. A bounded change may use verification only when a documented causal assessment identifies the affected characteristics and a predeclared minimum evidence set confirms substrate and feedstock genealogy, calibrated energy/feed/shielding and motion state, representative geometry and interface condition, actual deposition and interpass history, post-process execution, delivered-state chemistry, fusion, dimensions and properties, inspection capability and acceptance against existing limits. If that set is incomplete, its uncertainty overlaps a limit or the changed condition lies outside the validated domain, equivalence is not demonstrated and the route remains on hold.

Deviation handling preserves time and position. Feed interruption, nozzle obstruction, wire stubbing, arc instability, shielding loss, temperature excursion, collision, path pause, fixture motion, geometric anomaly, monitoring alarm, heat-treatment excursion, machining non-clean-up, NDT indication or missing data creates a hold. Rework or local redelivery is permitted only when its effect on microstructure, dilution, stress, geometry and inspection is qualified.

The qualification file lets an independent reviewer reconstruct why the actual component was accepted. It includes requirements, risk analysis, substrate/repair genealogy, feedstock and utility releases, equipment/calibration, build/path/version, operator authority, deposition and interpass records, monitoring, as-deposited release, post-process, final inspection/test, uncertainties, deviations and release authority. A supplier demonstration or literature wall is supporting evidence, not production qualification.

14. Conclusions and research priorities

Directed-energy deposition is a family of local-fusion processes, not a single performance class. Powder-fed laser DED, wire-fed laser DED and DED-Arc/WAAM have distinct feed, energy, shielding, geometry and safety states. Their common industrial challenge is coupling those states to a substrate whose thermal and metallurgical response evolves during deposition and remains in the product.

A defensible industrial programme follows six rules:

1. name and qualify the exact energy–feed–nozzle/torch–motion architecture instead of transferring a generic DED window;
2. release the substrate or repair component as a product material, with genealogy, preparation, interface and inspection evidence;
3. control energy, feed, pose, shielding, bead, dilution, path and interpass state as coupled variables rather than relying on a scalar heat-input surrogate;
4. keep as-deposited, heat-treated, separated, machined, finished and delivered states distinct;
5. validate monitoring against material and defect outcomes while retaining risk-based NDT and part-linked tests; and
6. compare routes using complete-cell accepted-part throughput, yield, machining, safety and authority to release.

Priority research should improve delivered powder- and wire-flow metrology; nozzle/torch state monitoring; multi-axis catchment and shielding maps; physics-based bead and dilution control; geometry-aware thermal models with uncertainty; robust interpass measurement; defect-labelled multimodal monitoring; correlation of signals with volumetric and interface defects; residual-stress prediction through release and machining; representative repair test artefacts; damage-removal and groove-family qualification; graded-composition delivery and phase prediction; large-part metrology and datum transfer; probability-of-detection studies for rough, curved and repaired regions; and interoperable part-data packages from deposition through post-processing.

Until those links close for a specified component and route, claims such as ‘any metal’, ‘any repair’, ‘high deposition rate’, ‘fully dense’, ‘isotropic’, ‘wrought-equivalent’, ‘zero waste’, ‘low cost’, ‘large-scale finished part’, ‘real-time quality assurance’ and ‘monitoring replaces inspection’ remain incomplete. Capability belongs to a qualified substrate–feedstock–energy–delivery–path–thermal–post-process–inspection–factory system.

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