

Material Jetting and Inkjet Additive Manufacturing

Droplet Generation, Multimaterial Capability, Support Strategy, Throughput and Factory Qualification

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Statement of Significance

Inkjet additive manufacturing is often reduced to a fluid-viscosity range, nominal dots per inch or a printer trade name. Those descriptors do not establish whether a production system ejects one stable primary drop from every required nozzle, places it at the intended coordinate, controls its spreading and coalescence, converts it to the required material state, removes support without damage and delivers an accepted component. Material jetting couples formulation, temperature, reservoir and recirculation state, pressure, printhead architecture, waveform, firing history, droplet flight, substrate interaction, pinning or phase change, cure, planarisation, multimaterial sequencing and post-processing. ER-143 provides a state-resolved comparison of UV-curable photopolymer, phase-change/wax, solution or suspension and multimaterial routes. It treats viscosity and dimensionless printability numbers as conditional descriptors rather than universal recipes; distinguishes CAD voxels from manufactured transition regions; and measures throughput only after support removal, conditioning and acceptance. This evidence architecture is essential for highly specialised resins, waxes and functional inks, whose claimed function cannot be separated from the head, waveform, cure and downstream route that manufacture it.

Keywords: *material jetting; inkjet additive manufacturing; drop-on-demand; piezoelectric printhead; waveform; droplet metrology; satellite droplets; wetting; coalescence; UV curing; phase-change wax; multimaterial; voxel; supports; process qualification*

Abstract

Material jetting creates three-dimensional objects by selectively depositing build-material droplets. Industrial implementations include piezoelectric drop-on-demand photopolymer systems, phase-change and wax routes, solution or suspension deposition and multimaterial platforms. These routes share droplet placement but not a single fluid window, solidification mechanism, support strategy or delivered material state. This qualitative engineering review follows the complete chain from released feedstock to accepted component. It examines material genealogy, temperature-dependent rheology, filtration and degassing, reservoir and backpressure state, actuation and channel acoustics, waveform/frequency interaction, droplet mass, velocity and direction, satellite formation, landing and spreading, inter-drop coalescence, pinning, UV conversion or phase change, layer levelling, multimaterial interfaces, supports, cleaning, post-cure, durability, geometry, surface, cell throughput, safety and change control. Published studies show why no scalar viscosity, surface tension, Z' value, nominal dpi or layer height can by itself qualify a process. Microfeature and surface results remain machine-, material-, orientation- and support-state-specific; multimaterial properties can depart markedly from ideal volume mixing; and photopolymer properties can change with conditioning and age. The proposed selection gate therefore requires head- and temperature-specific fluid evidence, strobed and statistical nozzle qualification, state-labelled line/layer/part measurements, full post-process validation and accepted-component throughput. Binder jetting, vat photopolymerisation, aerosol/electrohydrodynamic jetting, construction-scale deposition and final dense ceramic/metal qualification after green-body conversion are outside scope.

1. Purpose and scope

ER-143 applies the state-resolved selection framework of ER-139 to material jetting. ISO/ASTM 52900:2021 supplies the process-category vocabulary [1]. ISO/ASTM 52910:2018 structures design requirements [3], while ISO/ASTM 52920:2023 places qualification controls around the process and production site [2]. ISO/ASTM 52924:2023 provides traceable polymer-property classes [4]; ISO/ASTM 52927:2024 organises characteristics and test methods [5]; ISO/ASTM 52902:2023 addresses geometric capability through test artefacts [6]; and ISO 17295:2023 removes ambiguity from part-position and orientation reporting [7]. None of these standards declares that a named printer, resin, dpi or layer setting has qualified a component.

Material jetting deposits the build material itself. NIST describes continuous or drop-on-demand liquid deposition in which droplets build the structure and, in the photopolymer route, UV light creates the solid [8]. This distinguishes the category from vat photopolymerisation, where a light field selectively converts material held in a vat, and from binder jetting, where deposited liquid joins a separate powder-bed feedstock. A machine may use inkjet heads in more than one category, but the printhead component does not erase the material-flow boundary.

The review covers four overlapping industrial route families: jetted UV-curable photopolymers; phase-change or wax-like build/support materials; solution or suspension inks; and multimaterial/voxel-resolved platforms. Proprietary labels such as PolyJet and MultiJet identify particular implementations and must not be treated as universal technical definitions. Thermal, piezoelectric and other actuation principles also have different material-compatibility and reliability envelopes. The industrial focus is drop-on-demand piezoelectric delivery because it can address a broad range of non-aqueous and reactive formulations, but conclusions remain conditional on the selected head.

Within the Engineering Review series, ER-028 owns the rheology, waveform, satellite-formation and cure-timing physics of photopolymer inkjet [29]. ER-143 uses that prior work without re-owning it: its distinct remit is the production route and qualification architecture across the four route families, including non-photopolymer phase-change, solution and suspension states.

Highly specialised material families are in scope: rigid, tough, flexible, elastomeric, optical, transparent, high-temperature, dielectric, conductive, castable, sacrificial, wax, soluble/support, dental, otoplastic, microfluidic and other functional systems. The 3Dresyns inkjet platform records this declared portfolio breadth [27]. It is a commercial scope source, not independent proof of jetting stability, final properties, biological status, casting yield or production qualification. Aerosol jetting, electrohydrodynamic jetting, bioprinting, pharmaceutical dose qualification and construction-scale deposition are excluded. Particle-loaded inks are considered only through jetting and green-state control; debinding, sintering and dense ceramic/metal acceptance belong to the later specialised reviews.

2. Route families and material-state transitions

Droplet placement is the common action; the material transition is not common. A UV-curable route ejects low-viscosity reactive liquid, permits controlled landing and merging, applies a pinning or layer cure, then completes conversion through in-machine and/or final post-cure. A phase-change route conditions a melt for jetting and establishes geometry by cooling or crystallisation. A solution route loses solvent through evaporation or extraction. A suspension deposits a carrier plus dispersed phase and may require drying, binder removal or thermal consolidation. A multimaterial route coordinates two or more of these streams, sometimes with a separate support stream.

Drop-on-demand actuation ejects material only where commanded. Continuous inkjet forms a stream and deflects selected drops while unused material may be recirculated. These architectures differ in fluid residence, recovery, contamination risk, duty cycle and control logic. NIST explicitly recognises continuous and DOD deposition within material jetting [8], while its precision-deposition work demonstrates the adaptability of DOD for picolitre solution placement [9]. Neither architecture is intrinsically more qualified; the evidence must follow the implementation and delivered state.

Piezoelectric DOD couples an electrical waveform to actuator deformation, channel acoustics and nozzle flow. Thermal DOD nucleates a vapour bubble and can impose different thermal/material restrictions. Valve, acoustic or pneumatic dispensing can place larger droplets or different rheological classes but changes spatial resolution and dynamic response. A platform description must therefore identify actuation, chamber/nozzle geometry, recirculation, allowable temperature, compatible chemistry and the actual deposited-volume range rather than use `inkjet` as a complete specification.

Table 1. Route-specific opportunities and control burdens

Axis	UV-curable photopolymer DOD	Phase-change or wax jetting	Solution or suspension jetting	Multimaterial / voxel-resolved jetting
Deposited state	Reactive liquid drop followed by pinning/cure	Conditioned melt followed by cooling/phase change	Carrier plus dissolved/dispersed functional material	Two or more coordinated build streams, often plus support
Conditional opportunity	Fine selective placement, smooth surfaces and rapid local solidification	Fast physical setting, sacrificial/castable patterns and removable support options	Functional chemistry, particulate or thin-feature deposition	Local colour, stiffness, optical or functional variation and integrated interfaces
Characteristic limit	Temperature/rheology, oxygen, cure inhibition, bleed, shrinkage and ageing	Thermal history, crystallisation, distortion, remelt and fragile handling	Evaporation, clogging, agglomeration, sedimentation, drying stress and downstream conversion	Registration, cross-contamination, purge burden, interface width and non-ideal mixed properties
Support implication	Separate gel/soluble stream or same-family support; washing/dissolution can affect surface	Melttable or dissolvable wax-like support; access and thermal removal matter	Support bath, sacrificial ink or route-specific substrate strategy	Support compatibility must be proven against every build material and interface
Minimum metrology	Temperature, waveform, drop state, dose/irradiance, conversion and post-cure	Melt temperature, drop state, cooling/phase response and dimensional stability	PSD/agglomerates, stability, filter, drop state, drying and green-body integrity	Nozzle registration, material cross-talk, transition geometry and interface properties

The route name does not predict accepted throughput. A UV lamp can pin a swath quickly while the carriage, levelling blade, support wash or post-cure limits the cell. A wax can solidify without chemical cure yet require controlled melting, cleaning or investment-casting operations. A functional suspension can place very small quantities while filtration, nozzle recovery, drying or sintering determines factory output. A multimaterial system can eliminate assembly only if its printed interfaces and downstream operations meet the component specification.

3. State-resolved production chain

Production begins at material release, not at the first fired drop. Identity, version, lot, storage, age and container history are checked. The material is homogenised, filtered, degassed, dried, diluted or temperature-conditioned only as required by the validated route. Reservoir, recirculation and pressure state are established. The head reaches thermal equilibrium; nozzle condition is verified; the approved waveform and firing regime are loaded; and drop mass, velocity, direction, satellites and missing/weak jets are assessed. The substrate or prior layer is then prepared for landing.

During building, the system traverses or indexes the head, deposits model and support drops, permits spreading and coalescence, pins, cures, cools or dries them, and may level the layer mechanically. It repeats this cycle while managing pauses, first-drop history, material switching, purging and head maintenance. The completed green or partially converted object is

removed, support is melted, dissolved, washed or mechanically cleared, and the component is cleaned, dried, post-cured or conditioned. Only then is geometry, surface, cleanliness, material state and function inspected for acceptance.

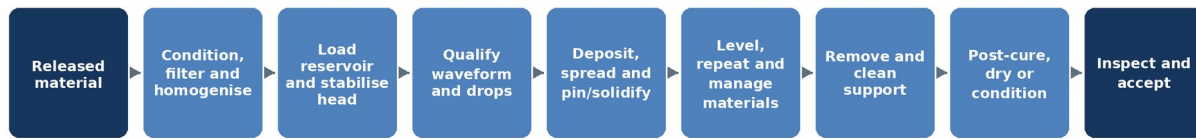


Figure 1. State-resolved material-jetting production chain

Each measurement must carry its state. Reservoir viscosity does not describe fluid at the heated nozzle. A strobed image at low frequency does not qualify the production firing pattern. A line on a reference substrate does not establish spreading on a partially cured layer. A component dimension before support removal does not establish the washed dimension. A tensile specimen after uniform post-cure does not automatically represent a shaded multimaterial interface or a fluid channel that retained support.

This chain also defines material genealogy. Liquid can undergo thermal residence, light exposure, volatile loss, oxygen uptake, moisture change, contamination, pigment or particle migration, polymerisation, filter loading and shear history. Returned or recirculated material is not automatically identical to virgin feedstock. A release-and-return rule must identify permitted residence, top-up, blend, filtration, sampling, recovery and discard criteria. The rule is especially important when a machine uses sealed cartridges that obscure rather than remove the internal history.

4. Fluid, suspension and feedstock identity

The formulation record must include the exact grade and revision; carrier, reactive species, photoinitiator, inhibitor, colourant, surfactant, wax, polymer, dissolved solid, particles and other functional additives; batch and storage history; and the measured attributes that control the selected head. Viscosity must state temperature, method and shear conditions. Surface tension must state method and time dependence where relevant. Density, volatility, moisture, oxygen sensitivity, electrical behaviour, particle/agglomerate distribution and chemical compatibility are added when they can alter delivery or the final state.

Viscosity is strongly temperature dependent in many jettable systems. The printhead, reservoir, lines and environment can occupy different temperatures, and firing adds local dynamic history. A result reported at room temperature cannot qualify a head operated at another temperature. Conversely, heating a material into a nominal viscosity range can accelerate reaction, evaporation, inhibitor loss, sedimentation changes, material attack or nozzle-plate wetting. Thermal conditioning therefore needs a defined ramp, soak, measurement location, tolerance and maximum residence.

Surface tension influences meniscus stability, ligament break-up, satellites and landing, but a scalar equilibrium value does not describe dynamic surface adsorption during microsecond-scale formation. Wetting at the nozzle plate, internal channel and substrate can differ. Density enters inertia. Elasticity, extensional response or particulate interactions can matter even when shear viscosity appears acceptable. The previously used example ranges of '2–20 mPa·s' and '30–35 mN/m' belong to a specific head, formulation and temperature context; they are not universal material-jetting acceptance limits.

Dimensionless groups help organise the coupling. With characteristic nozzle or drop scale 'a', velocity 'v', density 'rho', surface tension 'gamma' and dynamic viscosity 'eta':

$$Z = \sqrt{\rho \times \gamma \times a} / \eta = 1 / Oh$$

$$Re = \rho \times v \times a / \eta$$

$$We = \rho \times v^2 \times a / \gamma$$

'Z' relates inertial/capillary response to viscous damping; Reynolds and Weber numbers compare inertia with viscosity and surface tension. Jang et al. reported stable printability over '4 ≤ Z ≤ 14' for their investigated fluids and apparatus [15]. That result is valuable evidence of interaction, not a universal pass band. Head geometry, waveform, wetting, air, material elasticity, particles, temperature, frequency and desired drop outcome can move practical boundaries [14–16].

Suspensions require control of the complete particle and agglomerate population. A primary particle label does not reveal soft agglomerates, hard contamination or tails that encounter the filter and nozzle. The release record should include PSD method and basis, maximum or upper percentile justified for the flow path, solids fraction, dispersion state, settling/creaming rate, redispersibility, filtration sequence, filter compatibility and time-dependent viscosity. Recirculation may reduce settling yet increase shear/heat exposure or filter loading. Seerden et al. demonstrated the formulation burden for direct inkjet ceramic green bodies [17]; the result does not turn a deposited green body into a qualified dense ceramic.

5. Printhead, waveform and droplet metrology

A waveform is part of the manufacturing procedure. In a piezoelectric head, pulse amplitudes, rise/fall times, dwell, echo or cancellation segments and repetition timing drive the actuator and the acoustic pressure history inside the channel. Wijshoff describes the coupled electrical, mechanical, acoustic and fluid domains, including adverse effects of nozzle-plate wetting and air

bubbles [16]. The same nominal voltage and frequency can behave differently after material, temperature, fill pressure, head or channel condition changes.

Backpressure or meniscus pressure must retain fluid without air ingestion or uncontrolled weeping. Recirculation, reservoir level, filters, dampers and tubing affect this state. Firing history also matters. The first drop after a pause can differ from a steady train; adjacent channels can couple; resonances can make mass and velocity nonlinear with frequency. Verkouteren and Verkouteren measured frequency-, pressure- and droplet-number effects even in a carefully controlled DOD system [12]. Qualification should therefore test actual production bursts, pauses, accelerations and frequencies rather than one isolated drop.

Strobed imaging should measure or classify primary-drop volume or mass, velocity, trajectory, ligament break-off, satellites, coalescence in flight and timing at a controlled observation plane. A single attractive photograph is insufficient. The acceptance design needs nozzle-to-nozzle and time statistics, warm-up, pause/restart, duty-cycle extremes and a rule for missing, weak or directionally biased jets. NIST combines optical observation with gravimetric methods and reports near-percent relative uncertainty under its stated metrology conditions [10,11]. Later sub-picolitre work strengthens traceability between gravimetry and microscopy [13]. These methods demonstrate what can be measured; each factory must establish uncertainty suitable for its deposited-volume and geometry decisions.

Drop mass alone is not placement. Velocity affects flight time, aerodynamic disturbance and landing energy; directional error accumulates with throw distance; satellites can land outside the intended pixel; and mist or stray microdrops can contaminate optics, encoders or surfaces. Camera calibration must account for magnification, thresholding, depth of field, illumination timing and the conversion from a two-dimensional silhouette to volume. Where gravimetry averages many drops, the test plan must also show that the average represents individual and first-drop behaviour.

A printhead qualification is not permanent. Nozzle plates acquire residue; filters load; piezo response and channel state drift; UV stray light can gel reactive material; wax can crystallise; particles can settle or agglomerate; and cleaning can change wetting. Start-up, in-process and end-of-run checks require rational frequency. Automated nozzle substitution or compensation can preserve an image while changing local deposition and cure, so the compensation event belongs in the build record.

6. Flight, landing, spreading and pattern formation

The droplet leaving the nozzle is an intermediate state. Throw distance, head motion, substrate motion, air movement, electrostatic effects and timing determine where it lands. Registration across nozzle rows, printheads, passes and materials must be measured in the coordinate system of the part. Nominal nozzle pitch or dpi describes commanded sampling; it does not establish the realised spot, edge, wall, channel or interface.

After impact, inertia, viscosity, surface tension, contact angle, substrate energy, temperature, roughness and prior-layer cure govern spreading and recoil. Adjacent droplets may remain isolated, merge into a line, form a scalloped edge, bulge, bead or flood. The useful drop spacing is therefore coupled to drop volume and substrate state. A line test validates only its direction and local conditions; fills, corners, acute angles, small islands, thin walls and transitions expose different coalescence and heat/cure histories.

Pinning controls the time available for lateral flow. Too little pinning can produce bleed, rounded edges, colour/material cross-talk or local overbuild. Excessive early conversion can inhibit inter-drop or interlayer bonding and create a rough surface. Phase-change systems similarly balance rapid setting against internal stress, incomplete coalescence or remelt from later passes. Solution/suspension routes add evaporation, concentration gradients, coffee-ring-like redistribution, skin formation and drying stress. The material, substrate and timing sequence must be qualified together.

Planarisation can remove or redistribute excess, set layer height and expose fresh surface. It also introduces blade/contact mechanics, contamination and directional texture. Vidakis et al. found deposition angle and blade-motion direction relevant to surface response in one PolyJet study [23]. Udriou et al. proposed a surface-performance methodology for a material-jetting case [21]. Those results support orientation-aware measurement, not a universal roughness model.

Table 2. Mechanism-to-defect and evidence matrix

Mechanism or change	Possible visible result	Possible hidden consequence	Minimum evidence
Temperature or viscosity drift	Weak/missing jets, changed drop size, streaks	Dose/material-volume drift and non-uniform properties	Material/head temperature, time, viscosity method, nozzle statistics
Waveform/pressure/frequency mismatch	Satellites, direction error, weeping or air ingestion	Local under/over-deposition and intermittent defects	Production-regime strobed data, mass/velocity, pause/restart and pressure record
Nozzle contamination or material cross-talk	Streaks, colour contamination, ragged edges	Composition error at functional or multimaterial regions	Nozzle map, purge/clean record, chemistry-specific cross-contamination test
Uncontrolled landing/spreading	Bulges, gaps, rounded corners, poor lines	Trapped liquid, weak boundaries or dimensional bias	Drop-spacing matrix, line/fill/corner artefacts and prior-layer-state control
Pinning/cure imbalance	Bleed, tack, roughness or brittle layer boundaries	Conversion gradient, residual species and ageing sensitivity	Irradiance/spectrum/timing, conversion surrogate and final-state properties
Support contact/removal	Matte/granular surface, witness marks or damage	Residual support in channels and altered surface chemistry	Access coupon, removal parameters, residue/cleanliness and dimensional recheck
Non-ideal multimaterial interface	Blurred boundary or rounded inclusion	Property departure, weak interface and model error	Transition microscopy/metrology, interface tests and as-built geometry model
Ageing or conditioning change	Colour, tack, warp or surface change	Strength/modulus/function drift	Declared conditioning and time-resolved property programme

7. Pinning, cure, phase change and layer state

UV-curable jetting separates shape retention from final network conversion. A pinning exposure may stabilise droplets before the next pass; a layer exposure may consolidate a swath; final in-machine irradiation and post-cure can further change conversion, shrinkage, modulus, toughness, colour, optical transmission, residual extractables and temperature response. ‘Cured’ is not a sufficient state label unless the spectral irradiance, dose/timing, geometry, atmosphere, temperature and endpoint are defined.

Reactive liquid in flight and on the surface can receive intended and stray light. Cure too early and nozzle contamination or a weakly fused interface may result; cure too late and droplets move or materials mix beyond the design. Pigments, absorbers, fillers and functional molecules change optical penetration and kinetics. A formulation that jets stably can still fail during pinning. Conversely, a resin that cures well in a bulk or vat test can fail to jet because its rheology, wetting, volatility or thermal stability does not fit the head.

The deposited layer is thermally and temporally heterogeneous. Leading and trailing edges, first and last swaths, narrow and broad regions, shaded zones and support contacts can receive different delay and exposure histories. Machine speed or carriage order can therefore become a material variable. Qualification should map the usable field with representative shapes and include radiometry traceable to the relevant wavelength range, plus a conversion or property endpoint suitable for the application.

Phase-change materials replace chemical conversion with cooling, crystallisation or another reversible/irreversible transition. The chain still contains temperature gradients, shrinkage, latent heat, remelt, interlayer fusion and long-term dimensional stability. Wax patterns additionally become intermediate tooling for casting; accepted pattern geometry does not establish burnout, shell, metal fill or final-casting yield. The pattern and casting route require separate linked acceptance.

Solution and suspension deposits change as carrier leaves. Wet dimensions are not dry dimensions. A green body can shrink, crack, curl, develop porosity or redistribute solids. If later thermal conversion creates the final material, the printhead output is only an intermediate. The record must carry wet, pinned, dried, debound, sintered and conditioned states as applicable rather than attach final material claims to the liquid ink.

8. Multimaterial and voxel-resolved capability

Multimaterial jetting can place different feedstocks within one layer, blend commanded ratios or create mesoscale inclusions and gradients. The conditional benefit is substantial: colour, stiffness, compliance, refractive response, sacrificial regions, channels or local functions can be integrated without conventional assembly. Sitthi-Amorn et al. demonstrated a machine-vision-assisted platform designed for multiple materials [18]. That achievement does not imply that arbitrary chemistries share a head, adhere, cure together or remain dimensionally registered.

The CAD boundary is not necessarily the manufactured boundary. Drops spread, adjacent materials interpenetrate or displace one another, cure light crosses the intended interface, and planarisation can smear material. Purge and switching history can leave compositional carryover. Nozzle arrays and heads have registration errors. A nominal voxel is therefore a command element, not a guaranteed rectangular material volume.

Kornfeller et al. measured matrix–inclusion material-jetted specimens and found properties below a simple volume-weighted prediction; their tested mixtures were up to 33.9% softer than that idealised value, and modelling required non-ideal contact stiffness and as-built rounded inclusions [25]. The reported magnitudes belong to those materials and geometries, but the engineering conclusion is broad: interface and realised geometry must be measured. A digital-material label cannot replace tests at the relevant composition, transition width, direction, conditioning and load mode.

Material compatibility must address reservoir and head chemistry, thermal window, density and settling, mutual solubility, surface energies, cure spectra, inhibition, shrinkage, modulus contrast and post-process exposure. Support must remain selectively removable without extracting, swelling, cracking, staining or reacting with any build phase. A cleaning fluid compatible with one material can attack another. A post-cure that completes one network can embrittle or yellow its neighbour.

The design rule should specify the minimum independently resolvable material region, transition geometry, allowed cross-contamination and property uncertainty. Qualification coupons need straight and oblique interfaces, thin inclusions, enclosed boundaries, repeated material switching and the worst material contrast. Mechanical, optical, electrical, fluidic or biological endpoints must be measured on the final multimaterial state, not inferred from neat-material datasheets.

9. Supports, planarisation, surfaces and enclosed geometry

Material jetting often requires support because newly deposited drops and partially converted layers cannot bridge every overhang or cavity. The support may be a gel-like photopolymer, soluble material, wax or another sacrificial phase. Majca-Nowak and Pyrzanowski describe studied MultiJet and PolyJet implementations using different support materials and removal routes, including thermal removal for wax and water, mechanical or alkaline approaches for some photopolymer supports [20]. These are examples, not universal process definitions.

Support expands geometric freedom only where it can be deposited, stabilised and removed. Blind channels, lattices, narrow gaps, compliant membranes and rough internal surfaces can trap support or wash fluid. High-pressure water may damage thin features; heat can distort wax-sensitive geometry; alkaline or solvent exposure can swell, craze, extract or alter build material; mechanical tools can gouge surfaces. Access, flow path, diffusion length, temperature, time and agitation therefore belong to design and validation.

Support contact creates a distinct surface state. Matte and glossy machine modes, upward/downward/side faces, blade direction and support boundary can differ in texture and dimension. Silva et al. observed machine- and geometry-specific distortion at small material-jetted details and different surfaces with and without support [19]. Cazón et al., Udriou et al. and Vidakis et al. likewise show why tensile and surface results must retain orientation and process context [21–23]. A headline layer thickness or dpi cannot predict each surface.

Cleaning is a manufacturing operation. The record should identify support material and lot, removal equipment, fluid identity and condition, pressure/temperature/time, mechanical tools, bath loading, rinse, drying and acceptance. The test method must detect residues relevant to the application. Visual cleanliness can be inadequate for microfluidic, optical, electrical, bonding, coating, casting, dental or other specialist uses.

Planarisation and support interact with material balance. Removed model or support material becomes waste or contamination; blade wear and alignment affect thickness; a changed support formulation can change levelling and cure. The factory must track consumables, disposal, maintenance and recovery rather than treat support as free geometry. A design that technically prints but cannot be cleaned, inspected or economically processed is not an industrially feasible part.

10. Geometry, orientation and measurement uncertainty

Nominal dpi states address spacing, not final resolution. Drop diameter can exceed nozzle or address pitch; spreading enlarges it; coalescence and pinning alter edges; multiple passes and levelling alter thickness; cure or cooling changes volume; and support contact changes surface. Minimum positive feature, minimum negative gap, wall, hole, channel, corner radius, overhang, flatness and surface response must be measured separately.

Silva et al. found that more than 90% of their tested microdetails exceeded nominal dimensions; below machine-specific scales, geometry distorted and printing failed [19]. Their reported 423 micrometre distortion and 212 micrometre failure thresholds are not portable design rules. They demonstrate the need for a feature ladder tied to machine, material, orientation, support and measurement method. Majca-Nowak and Pyrzanowski measured local deviations beyond the mean dimensional response in several commercial material-jetting combinations [20], again showing that one accuracy number cannot represent every surface.

Orientation changes head-motion direction, layer staircase, support contact, cure delay, levelling interaction and mechanical loading relative to the layer system. ISO 17295:2023 should control coordinate and orientation reporting [7]. A study that reports ‘horizontal’ without the machine axes, head scan direction and specimen loading direction cannot be transferred reliably. ISO/ASTM 52902:2023 can support system geometric-capability artefacts [6], but production parts also require feature-specific and location-specific validation.

Measurement uncertainty must be compatible with tolerance. Optical measurement can be biased by transparency, gloss, edge threshold, support residue or refractive index. Contact probes can deform compliant materials. Computed tomography can lack contrast between similar photopolymers. Kornfellner et al. used optical coherence tomography and microscopy to resolve multimaterial geometry and showed that designed sharp cubes became rounded and directionally biased [25]. The metrology plan must select surface preparation, fixturing, environment and modality for the state being accepted.

Mechanical data also need real dimensions and conditioning. The cross-section of a tensile coupon should be measured rather than assumed from CAD. Orientation, support mode, cure, age, humidity and strain measurement belong to the report. Bochnia's long-term study of two PJM photopolymers found direction-dependent changes after approximately eight years, including reduced tensile strength for several cases and substantial modulus changes [24]. Those numbers are not universal ageing factors; they prove that durability cannot be inferred from as-printed values alone.

11. Highly specialised materials and direct/indirect routes

Specialised material jetting offers more than prototype appearance, but every added function increases the coupled control space. Rigid and tough photopolymers need final-state strength, strain, impact, temperature and durability evidence. Flexible and elastomeric materials require rate-, temperature- and time-dependent testing plus support-removal effects. Optical or transparent systems require haze, transmission, colour, surface and ageing after the qualified cure and cleaning. High-temperature, flame, dielectric, conductive, chemical-resistant or barrier functions need test methods and conditioning relevant to the intended environment.

Castable resins and waxes manufacture sacrificial patterns. Their smoothness and detail can be valuable, but final success depends on support removal, pattern stability, investment compatibility, burnout residue, thermal expansion, shell integrity, metal fill and casting finish. The accepted deliverable may be the pattern or the casting; the record must say which. No burnout-friendly label substitutes for a qualified casting cell.

Dental, otoplastic, microfluidic and biological-adjacent applications add cleanliness, extractables, dimensional fit, sterilisation or use-specific regulatory questions. ‘Dental’ is not one performance class, and biological acceptance cannot be inferred from a liquid formulation or a generic cured coupon. Internal channels require support and residue evidence. ER-086 owns analytical extractables and leachables from vat-printed photopolymers, and ER-095 owns photoinitiator migration and substitution; this review retains only the material-jetting route boundary. Patient-contact or regulated uses require their own risk management and validation outside this general review.

Conductive, optical, magnetic, ceramic, metal or other particle/function-bearing inks impose dispersion, filtration, stability, cure/dry and final-property burdens. A functional material can be jettable yet lose function during pinning, oxidation, solvent removal or post-cure. A concentrated high-performance paste designed for vat printing or mould injection is not automatically a

DOD ink. Head/nozzle geometry, PSD/agglomerates, solids loading, viscosity at jetting temperature, surface tension, carrier, filtration, waveform and conversion route must be disclosed and validated.

The 3Dresyns material and process-control pages organise photopolymer, wax, support, auxiliary and specialist families and state that results depend on the complete material–printhead–waveform–curing–post-process chain [27,28]. ER-143 adopts that control logic but treats the pages as declared portfolio/scope sources only. Product names, family descriptions and illustrative IFUs cannot serve as independent evidence of accuracy, property, safety or regulatory suitability.

12. Throughput, maintenance and factory economics

Print speed is not accepted throughput. The theoretical ejection capacity equals active nozzles multiplied by firing frequency and nominal drop volume, but a real build contains blank travel, carriage acceleration, pass overlap, multiple materials, support, pinning/cure, levelling, layer indexing, purge, nozzle substitution, inspection and maintenance. Geometry and tray packing change active duty. A high firing frequency that destabilises droplets or increases missing jets can reduce accepted output.

Effective cell throughput = accepted components / elapsed time from released material to final acceptance

Elapsed time includes conditioning, cartridge/reservoir handling, warm-up, head stabilisation, drop checks, build preparation, printing, support removal, cleaning, drying, post-cure or thermal treatment, conditioning, inspection, rework, maintenance and changeover. The numerator excludes rejected or quarantined components. Work-in-process inventory and queue time should be visible when comparing routes.

Multimaterial capability can consolidate assemblies, colours or functions and reduce downstream joining. It can also add cartridges, purge waste, head registration, compatibility validation, material-change cleaning and complex inspection. Phase-change support can simplify one removal route but introduce ovens and thermal handling. UV-curable systems can pin rapidly but still require wash/post-cure capacity. Solution/suspension systems can deposit functional material precisely while drying or conversion becomes the bottleneck.

Nozzle reliability creates nonlinear factory losses. One failing nozzle can create a repeating defect across a tray; aggressive maintenance consumes material and time; conservative preventive replacement costs heads. The economic record should include head life, filters, wiping/purge fluids, lamps, blades, supports, cleaning media, energy, waste, operator exposure controls, inspection and rejected-part cost. Availability must distinguish planned maintenance, recoverable nozzle events and failures that require intervention.

Cell design should balance parallel printers with downstream resources. A bank of fast printers feeding one support-removal station can create a queue and age partially converted parts. Cure chamber loading can produce spatial non-uniformity. Inspection can dominate high-mix production. The correct comparison is against an explicit alternative—vat photopolymerisation, powder bed, extrusion, machining, moulding, casting, assembly or no-build—not against an abstract claim of complexity-free cost.

13. Occupational safety, containment and waste

NIOSH states that additive-manufacturing hazards vary with the technology, material and environment and can include inhalation, dermal, fire, mechanical and ergonomic routes [26]. ER-143 does not convert that broad guidance into an inkjet-specific exposure limit. Each formulation requires its current SDS, chemical inventory, task analysis and applicable legal requirements. Enclosed cartridges reduce some handling but do not eliminate exposure during installation, leaks, purge, wiping, head cleaning, support removal, waste handling or maintenance.

Reactive photopolymers and cleaning chemicals can present skin and eye hazards; volatile carriers can create vapour and flammability concerns; fine particles or dried residues can become airborne; heated waxes and heads create thermal hazards; UV sources require interlocks and containment; pressure, motion and high-pressure cleaning create mechanical risks. The hierarchy of controls should favour closed transfer, enclosure, local capture where justified, interlocks, compatible tools and defined waste flows before relying on personal protective equipment.

Nozzle and support cleaning can aerosolise or spread material. High-pressure water, compressed air and ultrasonic or solvent cleaning require task-specific evaluation. Filters, wipes, purge fluid, failed prints, support, wash liquids and contaminated containers need compatible segregation and disposal. Water-washable does not mean suitable for uncontrolled drain disposal. Photopolymer or nanoparticle content can remain after dilution.

Fire and reaction boundaries require material-specific review of carriers, heated reservoirs, UV sources, electrical equipment and waste accumulation. Mixing materials or cleaners can create incompatibility. A seemingly small cartridge can generate repeated exposure during daily wiping. Maintenance procedures should specify de-energisation, UV isolation, pressure release, cooling, spill response and verification before restart.

Safety is part of qualification and change control. A formulation revision, higher temperature, new cleaner, larger tray, longer unattended run, altered ventilation, new support-removal station or higher production volume can change exposure. The factory record should connect risk assessment, engineering controls, training, inspection, incidents, waste and maintenance to the same configuration that produces accepted components.

14. Qualification architecture, selection gate and conclusions

ISO/ASTM 52920:2023 frames industrial AM as a controlled process and production-site system [2]. For material jetting, that system includes material genealogy, conditioning, reservoir and recirculation, head/nozzle state, temperature and pressure,

waveform/frequency, droplet evidence, motion/registration, substrate/prior-layer state, deposition, pinning/solidification, levelling, support, cleaning, post-cure/drying/thermal conversion, conditioning, measurement and disposition.

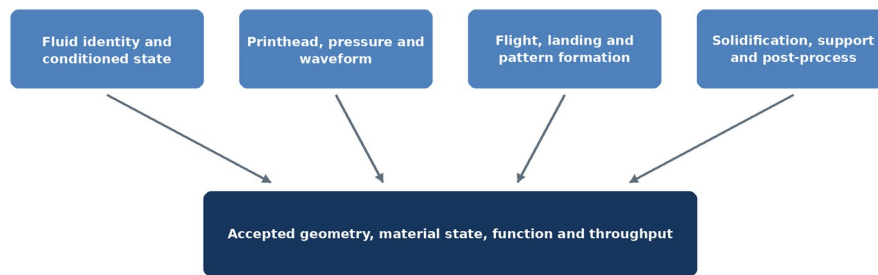


Figure 2. Coupled material-jetting production window

Table 3. Minimum industrial qualification record

Record block	Minimum controlled content	Release question
Material genealogy	Grade/revision, lot, composition or surrogates, storage, age, container/return history, viscosity method/temperature, surface tension, density and specialist tests	Was the exact material state released for this head and route?
Fluid path and head	Reservoir, filter, recirculation, pressure, tubing, head/nozzle model, temperature map, wetting/cleaning state and maintenance	Did every critical nozzle operate within the qualified delivery state?
Waveform and droplets	Waveform file/version, voltage/timing, frequency/duty, pause/restart, drop mass/volume, speed, direction, satellites, nozzle statistics and uncertainty	Does time-resolved evidence represent the production firing regime?
Deposition and conversion	Motion/registration, throw distance, substrate/prior-layer state, spacing/passes, pinning/cure/cooling/drying, levelling and monitored deviations	Was geometry built inside the qualified landing and solidification window?
Materials and support	Material map, switch/purge history, cross-contamination, support identity/contact/access and removal route	Are as-built transitions and cleaned internal features acceptable?
Final state and measurement	Cleaning, drying, post-cure/thermal route, conditioning, geometry, surface, cleanliness, properties, function and measurement uncertainty	Is the tested object the declared delivered state?
Factory and change	Software/configuration, calibration, environment, cell time, yield, rejects, waste, exposure controls, maintenance, deviations and equivalence decisions	Can each accepted component be linked to an unchanged qualified route?

Selection starts with the delivered component and proceeds through these gates:

1. Define geometry, surface, material, optical, electrical, thermal, cleanliness, durability, regulatory, functional, throughput and cost acceptance in the final conditioned state.
2. Classify the intended route: UV-curable, phase-change/wax, solution/suspension, multimaterial or another process. Eliminate routes whose material transition or support removal cannot create the state.
3. Qualify material/head compatibility at the real jetting temperature and residence history; do not transfer viscosity, surface-tension or 'Z' limits without the selected head and waveform.
4. Establish reservoir, pressure, filter, recirculation, head and nozzle controls. Characterise production-regime droplets statistically across nozzles, time, pauses and duty extremes.
5. Validate landing, drop spacing, lines, fills, corners, positive/negative features, materials, interfaces, support contacts, orientation, field position and worst geometry.
6. Qualify pinning, layer cure or phase change, levelling, cleaning/support removal, drying, post-cure or downstream conversion and final conditioning.
7. Demonstrate repeatability across lots, heads, operators, maintenance intervals, machines and time with measurement uncertainty compatible with acceptance.
8. Compare accepted-component throughput, yield, labour, material/support/purge waste, maintenance, exposure controls and full factory cost against a declared alternative, or issue a no-go decision.

The evidence base contains defined materials, heads and research systems. It does not provide universal viscosity, surface-tension, particle-size, waveform, voltage, frequency, temperature, drop-spacing, layer-height, cure, support-removal, accuracy, property or throughput settings. '4 <= Z <= 14', sub-500-micrometre feature observations, nominal dpi and supplier accuracy values remain study- or system-specific. Commercial pages identify portfolios and control logic but do not independently close performance claims.

The following conclusions control industrial use:

1. Material jetting is separate from vat photopolymerisation and binder jetting; printhead similarity does not collapse process categories.
2. Jettable material is a head-, temperature-, pressure-, waveform-, frequency- and time-dependent system state, not a bottle property.
3. Viscosity, surface tension and dimensionless groups organise investigation but cannot act as universal pass/fail rules.

4. Droplet qualification requires mass or volume, velocity, direction, satellites, missing jets and production-regime statistics.
5. Nominal dpi, nozzle pitch and layer height are input descriptors, not final feature size, accuracy or surface quality.
6. Landing, spreading, coalescence, pinning/cure or phase change, levelling and prior-layer state jointly manufacture geometry.
7. Multimaterial voxels and interfaces must be measured as-built; ideal CAD boundaries and linear property mixing are unsafe assumptions.
8. Supports and their removal are geometry, surface, cleanliness, labour, safety and waste operations inside the qualification boundary.
9. Highly specialised resins, waxes and functional inks require final-state proof after the qualified jetting and post-process chain.
10. Effective throughput is accepted components per complete cell time, with rejects, maintenance and downstream constraints included.

The correct decision may be photopolymer DOD, phase-change/wax jetting, a functional solution/suspension route, multimaterial jetting, another additive category, conventional manufacturing or no-build. The engineering output is a traceable accepted component or intermediate explicitly tied to its downstream route—not a nominally jettable liquid, a stable drop photograph or an unsupported printer claim.

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