

Polymer Material Extrusion for Industrial Production: Filament FFF/FDM, Pellet Extrusion and Reactive Deposition

Feedstock Control, Flow, Anisotropy, Throughput and Qualification

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Statement of Significance

Polymer material extrusion is often described as a simple operation in which a polymer is pushed through a nozzle and deposited layer by layer. That description hides the states that govern industrial performance. Filament, pellets and reactive thermoset feedstocks generate pressure differently; melting, shear and residence history alter the material before deposition; road geometry and thermal or reactive timing control bonding and shape retention; and supports, cooling, cure, finishing and inspection remain part of the production cell. ER-140 defines a state-resolved comparison of filament-fed thermoplastic, pellet-fed screw and reactive thermoset extrusion through melt-capable screw or large-format architectures. It explains why deposition rate is not accepted-part throughput, why bulk or feedstock properties do not qualify the printed component, and why anisotropy must be traced to geometry, contact, molecular or fibre orientation, crystallisation, cure and void state rather than assigned one universal correction factor.

Keywords: *material extrusion; fused filament fabrication; FFF; fused deposition modelling; FDM; pellet extrusion; granule extrusion; screw extrusion; reactive deposition; thermoplastics; thermosets; interlayer bonding; anisotropy; large-format additive manufacturing; process qualification*

Abstract

Polymer material extrusion includes materially different architectures that share selective deposition through a nozzle. In filament-fed systems, the solid filament is both feedstock and force-transfer element. Pellet-fed systems use a screw to convey, melt, mix and pressurise granules. Reactive thermoset systems within this review use a melt-capable screw or large-format extrusion head to convey, thermally condition and pressurise material before controlled gelation or cure during or after deposition. This qualitative engineering review compares those routes from released feedstock to accepted component. It examines conditioning, feeding, melting or mixing, pressure generation, nozzle flow, bead placement, transient starts and stops, inter-road contact, molecular interdiffusion, crystallisation, chemical conversion, fibre orientation, cooling, support removal, finishing, inspection and change control. Primary studies show that bond formation occupies a short thermal window, extrusion can orient and disentangle polymer chains, semi-crystalline transformations can restrict welding, and increased flow changes feature scale, thermal history and motion demand. Pellet and filament routes can produce similar extrudates without producing equivalent parts, while reactive screw or large-format extrusion introduces feed-state, residence, gel-time, exotherm and cure-shrinkage constraints. Large-format and reinforced-polymer routes can increase deposition capacity or stiffness within bounded applications, but may intensify anisotropy, void, surface, nozzle-wear and machining burdens. The resulting selection gate uses accepted-component requirements and complete-cell throughput rather than machine headline values. Construction printing, concrete and macroscopic high-volume production are outside scope.

1. Purpose and scope

ER-140 applies the state-resolved framework of ER-139 to polymer material extrusion. The relevant decision is not whether a machine can move a nozzle through the required toolpath. It is whether a controlled combination of feedstock, metering architecture, thermal or reactive history, deposition strategy, cooling or cure, recovery, finishing and inspection can repeatedly deliver the required polymer state and geometry.

ISO/ASTM 52900:2021 supplies the common process vocabulary [1]. ISO/ASTM 52903-1:2020 and 52903-2:2020 address plastic feedstock and process equipment for material extrusion [2,3]. ISO/ASTM 52920:2023 places the route inside an industrial process and production-site qualification system [4]. These documents create necessary control categories. They do not establish that a nominal polymer, machine or parameter set is qualified for a particular component.

The review covers thermoplastic filament extrusion, pellet or granule-fed screw extrusion and reactive thermoset extrusion only where a melt-capable screw or large-format extrusion head performs bulk conveying, thermal conditioning and pressure generation. The hardware and feed state define the boundary: premixed or independently metered non-molten inks and pastes delivered from cartridges, syringes, reservoirs or pumps, including two-part static- or dynamic-mixer routes, belong to ER-144. It includes fine and large-format polymer systems when the intended product is a polymer component, preform or tool. It excludes concrete, cementitious materials, geopolymers, regolith and construction printing. Silicone-like elastomers made by selective conversion in a vat are a separate VPP category addressed in ER-102 [28]. Bound-metal and bound-ceramic extrusion belong to ER-148 and ER-154 because debinding and sintering determine their delivered material states. Functional nano/micron and

continuous-fibre systems receive only the boundary treatment needed to explain process effects; their specialised functions are addressed in ER-156-ER-161.

2. Three architectures inside one process category

Material extrusion describes selective material dispensing through a nozzle or orifice. It does not define how pressure is generated, whether the feedstock is melted or chemically transformed, or when the deposited road becomes dimensionally stable. Those distinctions control both the operating window and the evidence required for release.

In filament-fed thermoplastic extrusion, a drive mechanism pushes a solid filament into a heated liquefier. The filament acts as a packaged feed geometry and, within the operating window, transfers force to the melt. Its diameter, ovality, stiffness, surface condition, moisture and traction affect delivery. High pressure, insufficient heating or low column stability can cause slip, grinding or buckling. The architecture can support relatively compact metering hardware, but its rate is jointly limited by traction, heat transfer and motion rather than by commanded speed alone [14].

Pellet-fed extrusion separates feed geometry from the final road scale. Pellets enter a gravity-fed or forced-feed system and a screw conveys, compresses, melts, mixes and pressurises the polymer. This can remove filament-making as an upstream conversion and can support higher mass flow or in-line compounding. It also creates new controls: pellet size distribution, bulk density, bridging, dosing, screw design, barrel-zone temperatures, back pressure, residence-time distribution, melt completion, purging and degradation.

Reactive thermoset extrusion within ER-140 uses a melt-capable screw or large-format extrusion head for bulk conveying, thermal conditioning and pressure generation before gelation or cure contributes to shape retention. Components may be combined upstream, but cartridge-, syringe-, reservoir- and pump-fed paste routes with static or dynamic mixing are outside this review and are treated in ER-144. The process window links released feed or premix state, screw or extruder residence, temperature, viscosity, initiation, layer time, exotherm and shrinkage. The extrudate can collapse before gelation, distort from reaction heat or form a weak interface if the receiving surface has advanced too far in conversion [19].

Table 1. Filament, pellet and reactive extrusion are different production architectures

Axis	Filament-fed thermoplastic	Pellet-fed thermoplastic	Reactive screw/large-format thermoset extrusion
Released feedstock	Qualified filament spool or cartridge	Qualified pellets/granules, blend or compound	Qualified thermoset feed or premix, catalyst/initiator state and extrusion set
Pressure generation	Driven filament transfers force into liquefier	Rotating screw conveys, melts and pressurises	Melt-capable screw or large-format extrusion head conveys, conditions and pressurises
Main transformation	Heating and melt flow, then cooling/solidification	Conveying, melting, mixing and pressurisation, then cooling	Bulk conveying/thermal conditioning, deposition, gelation and cure
Main conditional opportunity	Compact feed system and controlled packaged geometry	Direct pellets, compounding potential and higher mass-flow range	Access to non-remeltable polymer networks and in-situ cure
Characteristic limitation	Traction, buckling, diameter tolerance and conductive-heating limit	Bridging, dosing, incomplete melting, pulsation and residence history	Feed-state drift, residence/reaction coupling, exotherm, collapse, cure gradient and cleaning
Required change-control focus	Spool/lot, diameter, moisture, drive and liquefier state	Pellet lot, drying, dosing, screw/barrel state, purge and residence time	Feed/premix lots, screw/extruder, thermal activation, gel/cure state, purge and cleaning

3. State-resolved process chain

The state chain starts before the printer and ends after acceptance. Feedstock is released against identity and handling criteria, conditioned, loaded and metered. The material is then heated, sheared, mixed or activated; pressurised through the nozzle; placed as a road; joined to the previous road or layer; cooled, crystallised or cured; recovered from the platform and supports; finished; conditioned; inspected; and released. Each transition can create a defect that a later operation cannot remove.



Figure 1. State-resolved polymer material-extrusion chain

The route record must identify the state represented by every measurement. Melt viscosity measured on virgin pellets is not the viscosity after drying, repeated residence or in-line mixing. Tensile data from a filament or moulded plaque do not represent an interface-dominated printed orientation. A dimension measured while the component is warm does not represent the conditioned dimension. A thermoset part described as printed may still contain incomplete conversion or a thermal gradient. Industrial control depends on preserving those distinctions.

4. Feedstock release and conditioning

Feedstock identity is more than polymer name. For filament, the minimum record includes formulation and reinforcement, supplier and lot, nominal and measured diameter, ovality where relevant, spool history, storage, moisture conditioning and any observed brittleness or surface contamination. Diameter variation changes delivered volume when a motion command assumes a fixed cross-section. Stiffness and friction affect traction and buckling. A filament that passes a bulk-material certificate can still fail as a force-transfer element.

Pellet records add particle-size range, shape, fines, bulk density, bridging tendency, blend uniformity and dosing method. Segregation can change filler fraction or colour during a build. A screw can mix some fluctuations but cannot convert an uncontrolled blend into a qualified compound. Direct pellet use may avoid a filament-extrusion history, yet the complete degradation comparison must include pellet drying, barrel residence, purge, start-up scrap and any in-line recycling. La Gala et al. showed for the studied ABS and PLA systems that comparable extrudates from different processing routes did not guarantee comparable specimens [17]. The correct conclusion is route-specific equivalence testing, not an inherent pellet or filament ranking.

Moisture is a material and process variable. It can cause bubbles or surface disruption, change melt rheology and promote hydrolysis in susceptible polymers at processing temperature. Drying temperature and duration are not transferable between polymers or packages. The record should include the conditioning equipment, load, time, temperature, dew point or other accepted endpoint, time from dryer to extruder and exposure during pauses. Re-drying and repeated thermal history require change control when they can alter the feedstock.

Reactive screw or large-format feedstocks require control of the supplied component or premix identities and of the state released to the extruder. Viscosity, filler suspension, inhibitor or initiator state, temperature, storage age and contamination can alter both flow and conversion. Independent-stream ratio and mixer qualification belongs to the cartridge-, pump- and mixer-defined route in ER-144. ER-140 instead requires evidence that priming, extruder residence, reaction advance and shutdown waste remain separated from acceptable deposition.

5. Metering, melting, reaction and nozzle flow

The extrusion command is not proof of delivered flow. In filament systems, commanded feed can diverge from actual flow through drive slip, filament compression, liquefier pressure, incomplete heating or transient storage of elastic melt. Go et al. identified traction force, conduction into the filament core and motion capacity as coincident system limits [14]. This means that increasing feed command can produce under-temperature extrusion, pressure growth or intermittent slip before it produces acceptable higher throughput.

The nozzle flow is non-Newtonian and viscoelastic. Shear rate, temperature and residence history change apparent viscosity and pressure drop. Entrance and corner flow can stretch and orient molecules; McIlroy and Olmsted modelled strong deformation and reduced entanglement density under one amorphous-polymer FFF geometry [13]. That result supports a molecular-state control question. It does not establish a universal loss of entanglements for all polymers or nozzles.

In a screw extruder, screw geometry, rotation, barrel temperature and back pressure determine conveying, melting and mixing. A high nominal screw capacity is irrelevant if pellets bridge, melt incompletely, degrade during slow regions or produce pressure pulsation. The start-up, pause and shutdown states can differ from steady operation because residence time and temperature change while motion stops. Purge identity and duration therefore belong to the build record. Amirahmadi et al. demonstrated screw-extrusion processing of fibre-reinforced high-temperature thermoplastics within one defined system [18]; the evidence supports feasibility and process coupling, not transfer of its window to another material or screw.

Reactive extrusion adds reaction kinetics to the flow history. In the vinyl-ester route studied by Romberg et al., layer time relative to gel time separated collapse, an intermediate exotherm-driven flow behaviour and warpage [19]. Forced convection changed stability in that bounded experiment. The transferable rule is that flow, reaction heat and shape retention must be controlled together. A single room-temperature reaction-time value is not a process window because feed preparation, extruder residence, bead temperature, substrate temperature, section thickness and accumulated heat can alter local conversion.

Nozzle condition is a controlled machine state. Filled polymers can erode or enlarge a nozzle, changing flow area, road geometry and the relation between command and deposited mass. Bianchi et al. associated progressive nozzle wear with surface and mechanical changes for the studied short-carbon-fibre polyamide [23]. A maintenance interval therefore requires evidence from the actual feedstock-nozzle pair or a conservative inspection rule; generic printing hours are insufficient.

6. Road geometry, placement and dimensional control

A deposited road is not an ideal rectangular voxel. Its width and height reflect nozzle geometry, gap, flow, speed, pressure, temperature, wetting and the deformation imposed by the receiving surface. Adjacent roads can overlap, leave designed or unintended gaps, or displace earlier material. Corners and acceleration zones change instantaneous speed and pressure demand. Starts, stops, retractions and seam positions create local histories that steady straight-line coupons do not represent.

Road scale is a coupled selection variable. A larger nozzle or bead can increase volumetric deposition under suitable heating and motion capacity, but it also changes minimum wall, corner radius, surface stair-step, local heat input, cooling time and machining allowance. A smaller road can improve access to fine features while increasing path length, starts and stops, and machine occupancy. The usable setting is bounded by final geometry and acceptance, not by nominal resolution or maximum flow in isolation.

Dimensional control must include build-platform adhesion, thermal contraction, crystallisation, cure shrinkage, residual stress and support interaction. High chamber or substrate temperature can extend the welding window and reduce thermal gradients, but it can also change sag, crystallisation, cycle time, energy use and removal conditions. The qualified dimensional state is the conditioned component after required annealing, support removal and finishing.

7. Bond formation and anisotropy

Thermoplastic road bonding requires intimate contact followed by molecular mobility across the interface. Bellehumeur et al. modelled contact and bond formation between deposited polymer filaments [9]. Sun et al. measured how deposition strategy and thermal boundary conditions affected cooling, mesostructure and bonding for their studied polymer system [10]. Seppala and Migler used calibrated infrared thermography to show that the weld zone can pass through its useful elevated-temperature state rapidly [11]. Coogan and Kazmer further separated contact, wetting and diffusion as contributors to bond strength in their ABS experiments [12].

These studies reject two shortcuts. First, nozzle temperature alone does not define interface temperature because travel time, previous-layer temperature, chamber conditions and geometry contribute. Second, a void-free external surface does not prove molecular continuity. Thermal history based prediction can support process development, as shown by Mahmoud et al. for a bounded material-extrusion study [22], but a model must be validated against the actual material, geometry and measurement endpoint.

Semi-crystalline polymers add crystallisation to the competition. Crystallisation can increase stiffness and change shrinkage while restricting chain mobility available for welding. Baouch et al. reported flow-enhanced crystallisation restricting welding in the studied polypropylene process [21]. Comelli et al. examined PEEK filament before and after FFF extrusion and showed why processing history belongs to material characterisation [20]. The factory cannot infer equivalent welding from similar nozzle temperature when crystallisation kinetics, molecular weight, thermal history or cooling environment differ.

Printed anisotropy is not one property. It can arise from road orientation, interface density, incomplete contact, void distribution, polymer-chain orientation, crystallite morphology, short-fibre alignment, thermal gradients and local path features. Ahn et al. measured orientation-dependent properties for defined ABS specimens [8]. Duty et al. observed voids, imperfect fusion and interface-associated failure in early BAAM materials [16]. Those data demonstrate mechanisms and bounded magnitudes; they do not justify applying one reduction factor to another printer, polymer, bead scale or load case.

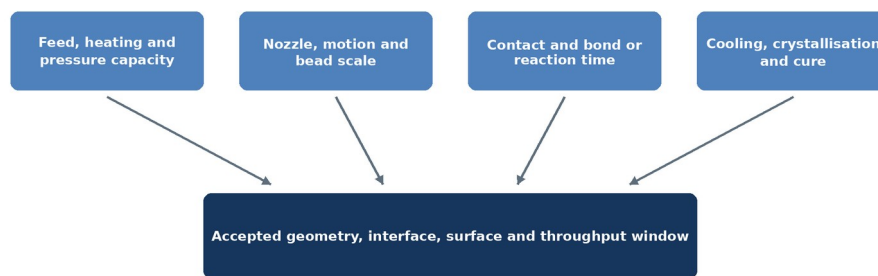


Figure 2. Coupled deposition, bonding and shape-retention window

Table 2. Mechanism-to-defect and evidence matrix

Process stage	Controlling variables	Representative unacceptable state	Evidence needed for control
Feed and conditioning	Identity, lot, diameter or pellet distribution, moisture, blend uniformity	Slip, bubbles, segregation, hydrolytic loss, variable flow	Incoming inspection, conditioning record, mass/diameter or dosing data
Melting or activation	Temperature, pressure, screw/drive state, feed or premix state and residence	Incomplete melt, degradation, out-of-state feed or premature reaction	Temperature/pressure trend, purge rule and released-feed verification
Nozzle flow	Rheology, shear, wear, obstruction, transient response	Under-extrusion, pulsation, changed bead width, oriented or degraded state	Delivered-mass check, road measurement, nozzle inspection, transient test
Placement and contact	Gap, speed, acceleration, path order, substrate state	Gaps, excessive overlap, poor contact, displaced road	Toolpath revision, geometry map, in-process image or dimensional evidence
Welding or reaction	Interface temperature/time, diffusion, crystallisation, gel/cure	Weak interface, collapse, exotherm-driven flow, conversion gradient	Thermal/reactive history plus orientation-specific destructive evidence
Cooling and recovery	Chamber, supports, contraction, anneal, removal method	Warping, residual stress, damaged surface, inaccessible support	Conditioned dimensions, removal verification, thermal/post-process record
Final acceptance	Environment, orientation, surface, internal voids, intended load	Coupon passes while component-critical feature fails	Part-linked sampling, traceable tests and application-specific acceptance

8. Scale, reinforcement, supports and finishing

Large-format polymer extrusion changes the size of the heat source, bead, unsupported span and machining allowance. Love et al. identified short carbon fibre as an important enabler in one large-scale polymer AM development context [15]. Duty et al. showed that the deposited large-bead structure retained interface and void limitations despite its different scale [16]. The

conditional opportunity is higher deposition capacity for geometries that tolerate a large bead and planned finishing. It is not a general replacement for fine extrusion, moulding or machining.

Short fibres can raise stiffness, reduce some thermal distortion and change melt flow. They can also align along the deposition path, increase directional behaviour, obstruct small nozzles, abrade hardware and produce a rougher surface. Fibre loading by mass does not specify orientation, length after processing, voids or interface quality. The delivered composite must be tested in the relevant direction and conditioned state. Continuous-fibre co-deposition introduces additional placement, impregnation, curvature and load-transfer controls and is therefore not treated as a simple extension of short-filled filament in this paper.

Support strategy belongs to route selection. ER-163 owns the detailed qualification of supports for internal channels and sacrificial geometries; ER-140 retains only the route-selection boundary needed here. Breakaway support leaves contact marks and requires mechanical access. Soluble support introduces dissolution chemistry, time, bath capacity, waste and drying, and internal cavities remain unacceptable when dissolution or removal cannot be verified. Same-material supports may be simple to feed but can demand cutting, grinding or machining. For reactive systems, a support or surrounding medium can also alter heat transfer and cure. A geometry is not industrially printable merely because unsupported deposition can be simulated.

Finishing can include trimming, drilling, milling, sanding, sealing, coating, annealing or surface treatment. These operations may be necessary to reach tolerance, roughness, leak tightness or interface requirements. They also can expose internal voids, release dust, heat the polymer or remove the as-deposited skin. The production drawing and cost model must declare which surfaces are deposited, supported and machined.

9. Throughput, automation and factory economics

The machine deposition rate is one term in a complete-cell denominator. A useful route-specific definition is:

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

The elapsed boundary includes drying or feed preparation, loading, start-up and purge, building, planned pauses, cooling or cure, platform and support removal, finishing, conditioning, inspection, queue time and rework. A pellet system can increase steady mass flow while shifting the bottleneck to drying, machining or inspection. A filament system can automate spool handling while remaining limited by heat transfer or path length. A reactive screw or large-format route can deposit rapidly but lose capacity through extruder cleaning, cure occupancy or out-of-state scrap.

Automation must be evaluated by transfer state. Automatic toolpath execution does not automate feedstock release, moisture control, nozzle inspection, platform change, support removal, purge segregation, finishing or acceptance. A lights-out claim requires controlled detection and disposition of feed interruption, pressure drift, thermal deviation, bead error, collision, loss of adhesion and unsafe emission-control state.

The comparison against moulding, machining or another AM route must freeze annual volume, part mix, material and conditioning state, dimensional and surface acceptance, labour basis, equipment utilisation, yield and inventory assumptions. Tooling avoidance has value only when equivalent tooling would otherwise be required. Geometric freedom has value only when the application uses it. Pellet price cannot be used as component-cost evidence without processing yield and cell burden.

10. Occupational safety and containment

Polymer material extrusion combines heated surfaces, moving systems, pressure, hot polymer, decomposition products, ultrafine particles, organic vapours and post-processing dust or chemicals. Reactive routes add uncured components, catalysts or initiators, exothermic reaction and mixed-material cleaning. Reinforced feedstocks can introduce respirable fragments or dust during trimming and sanding. Risk assessment must follow the actual formulation and task.

Stefaniak et al. measured particles and organic vapours in four facilities using industrial-scale material extrusion and material jetting [25]. The personal exposures measured in that study were below the applicable NIOSH limits, while emissions still entered workplace air. This is facility-specific evidence. It neither proves safety for another material or ventilation state nor converts emission rate into operator dose without an exposure model. Where ultrafine-particle emission is a concern, the assessment must include number-based measurement; gravimetric dust alone can miss the controlling exposure signal.

NIOSH Publication 2024-103 recommends applying the hierarchy of controls to printer selection, enclosure, ventilation, operation, maintenance and post-processing [26]. ISO/ASTM 52933:2024 provides a test method for hazardous substances emitted by material-extrusion printers in non-industrial places [6]. ISO/ASTM DIS 52961 remained under development at stage 40.99 (DIS approved for registration as FDIS) on 5 September 2026 and must not be cited as a published requirement [7]. Reactive thermoset cells must also treat heat accumulation and self-accelerating reaction in a stalled extruder or mixer, dead volume or interrupted line as a credible runaway and fire scenario; the system must be de-energised and the affected material safely purged before restart under an approved procedure. Factory qualification should record enclosure and exhaust state, filter identity and change interval, task locations, cleaning methods, hot-work and burn controls, and the basis for any exposure assessment.

11. Qualification architecture and change control

ISO/ASTM 52920:2023 places production-site capability, process control and evidence management around the machine [4]. NIST likewise treats AM part qualification as an evidence problem spanning process physics, measurement, material data and modelling rather than as an automatic consequence of machine category [27]. ASTM F3489-23 identifies material handling, anisotropy, porosity, orientation, build location, conditioning and test environment as variables relevant to static mechanical

evaluation of MEX polymers [5]. The standards do not make a coupon equivalent to a component. They identify what must be recorded and bounded.

The minimum process specification should control feedstock and conditioning; machine, drive or screw configuration; nozzle identity and wear limit; software and toolpath revision; barrel, nozzle, chamber and platform temperatures; pressure or delivered-flow indicators; road width/height and layer strategy; starts, stops and seams; support and recovery; cooling, cure and anneal; finishing; inspection; and acceptance. The record must distinguish commanded values from measured or verified states.

In-process measurement should target a causal variable. Read et al. demonstrated online measurement for parameter discovery in FFF [24]. Temperature, pressure, motor load, delivered mass, bead geometry or imaging may be useful, but recording a signal is not qualification unless its relation to an unacceptable state and its action limits are established. A thermal trace that cannot distinguish an interface defect, or a camera that does not cover the critical region, is monitoring evidence rather than acceptance evidence.

Change control must assess material formulation or supplier, filament diameter, pellet distribution, drying, reinforcement, colourant, nozzle material or diameter, drive or screw, heater, sensor, firmware, slicing software, road scale, path order, chamber state, platform, support, reactive feed or premix state, cure schedule, finishing and test method. A change can be equivalent only when the causal characteristics controlling the accepted component remain inside the validated boundary.

Table 3. Minimum industrial qualification record

Record block	Minimum controlled content	Release question
Feedstock	Identity, lot, composition/reinforcement, geometry, storage, moisture and conditioning	Was the released material in the validated feed state?
Metering system	Drive/screw/extruder configuration, calibration, wear, temperatures and pressure or delivered-flow indicators	Was actual delivery controlled rather than only commanded?
Build definition	Geometry revision, orientation, bead/layer plan, starts/stops, supports and critical zones	Does the build record represent the tested configuration?
Thermal/reactive history	Nozzle/barrel/chamber/platform state, cooling, crystallisation, mix, gel and cure where applicable	Were bonding and shape-retention states inside the validated window?
Recovery and finishing	Cooling time, platform removal, support route, anneal, machining, cleaning and conditioning	Is the inspected object in the declared delivered state?
Measurement	Conditioned dimensions, surface, void/interface evidence, mechanical or functional tests and uncertainty	Do measurements address the component-critical failure modes?
Safety and containment	Enclosure/exhaust and filter state, particle-number or other justified exposure measurement, task controls, cleaning, waste and restart/purge controls	Were emissions, exposure and reactive-line hazards controlled for the actual task?
Acceptance and change	Part-linked disposition, deviations, rework, non-conformance and equivalence decision	Can every accepted part be traced to an unchanged qualified route?

12. Selection and no-go gate

Selection starts with the delivered component, not the cheapest feedstock or largest flow value. The gate is:

1. Define material state, geometry, surface, dimensional, mechanical, functional and environmental acceptance.
2. Eliminate routes that cannot meter, melt or react the required formulation through the declared architecture without unacceptable degradation or instability.
3. Verify road scale, support and recovery access, interface direction, cooling or cure, and inspectability.
4. Demonstrate the required properties in the critical build orientations and conditioned final state.
5. Close drying, purge, ventilation, finishing, maintenance, metrology and operator requirements.
6. Compare accepted-part throughput, yield and complete-cell cost against a declared conventional or additive route.
7. Define change-control limits or issue a no-go decision.

A filament route should be rejected when traction or heating cannot deliver stable flow for the required material and rate. A pellet route should be rejected when feed segregation, incomplete melting, residence variation or bead scale cannot be controlled. A reactive screw or large-format route should be rejected when released feed or premix state, extruder residence, gel/cure timing, exotherm or cleaning cannot be validated. Any route should be rejected when support removal or inspection is inaccessible, when critical directional performance cannot be met, or when the factory cannot control the exposure and post-processing state.

13. Limitations and research priorities

This review does not provide universal process windows, property tables, machine rankings or cost multipliers. Its cited experiments span different polymers, machines, bead scales and endpoints. They demonstrate causal mechanisms and evidence boundaries, not pooled qualification values. Large-format studies do not establish high-volume production, and emission measurements from one facility do not determine exposure in another.

Research priorities are: traceable measurements linking feed history to delivered flow; validated pressure, temperature and bead-state monitoring; molecular and crystallisation models connected to component-scale interfaces; pellet-feed and screw-residence measurements during transients; reactive-process models coupling flow, gelation, heat and shrinkage; part-level

orientation and void maps; nozzle-wear indicators; support-removal verification for internal features; and open accepted-yield datasets covering the complete cell rather than steady deposition.

14. Conclusions

Polymer material extrusion is a family of state-transforming production routes, not a single nozzle process. The following conclusions control its industrial selection:

1. Filament, pellet and reactive screw or large-format systems generate pressure and dimensional stability through different mechanisms and require different qualification records.
2. Feedstock release includes geometry, moisture, handling and process history; nominal polymer identity is insufficient.
3. Flow command is not delivered flow. Traction, heat transfer, pressure, residence, reaction and nozzle state can become the limiting mechanism.
4. Interlayer performance is created by contact, thermal or reactive history, molecular mobility, crystallisation, orientation and void state. No universal anisotropy factor is valid.
5. Increasing deposition rate changes road scale, heating, motion, bonding, cooling, surface and finishing. It is not a free productivity gain.
6. Large-format and reinforced extrusion can be advantageous for bounded polymer components or tooling, while adding interface, orientation, wear and machining burdens.
7. Accepted components per complete cell cycle, with yield and inspection included, is the relevant throughput denominator.
8. Qualification must link feedstock, metering system, build, thermal/reactive history, recovery, finishing, measurement, acceptance and change control.

The correct route may be filament, pellets, reactive screw or large-format extrusion, another AM process or no additive route. The engineering result is the controlled delivered component, not the machine category.

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