

Bound-Ceramic Material Extrusion: Filaments, Pellets and Pastes, Green Strength, Thermal Conversion, Shrinkage and Qualification

From a Released Powder-Binder Feed to an Accepted Sintered Ceramic

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Statement of Significance

Bound-ceramic material extrusion can shape oxide, non-oxide and functional ceramics on comparatively simple motion platforms, but the printer does not produce a finished ceramic. It deposits a highly filled powder-binder feedstock as roads that become a green body. That body must survive handling, binder removal and sintering before its composition, dimensions, flaws and properties can be accepted. The apparently simple sequence hides three distinct feed architectures. Filament-fed systems require tight diameter and ovality, sufficient flexibility for winding and routing, sufficient compressive stiffness to avoid buckling, controlled drive-wheel contact and predictable melting. Pellet- or granule-fed systems remove the preformed-filament constraint but add hopper flow, bridging, screw or plunger transport, residence-time and purge risks. Binder-continuous pastes can be included only when the binder phase controls shaping and green setting; colloidal, gel-forming and drying-dominant direct ink writing remains a separate route. In every architecture, solids loading, particle surfaces, binder composition, dispersion and thermal history create a coupled rheological and mechanical window. Nozzle diameter is not road resolution, nominal infill is not density, and a slicer oversize factor is not qualified shrinkage compensation. Bead and layer interfaces, trapped air, underfill, seams and support contacts can persist as fracture origins after the binder has disappeared. Debinding is geometry-dependent mass transport and decomposition, while sintering creates direction-, geometry- and furnace-load-dependent shrinkage. This review connects feedstock release, feed manufacture, extrusion, green handling, debinding, sintering, finishing, brittle statistics, safety, economics and qualification. It provides no transferable composition, temperature, speed, nozzle, raster, debinding schedule, sintering cycle or scale factor.

Abstract

Ceramic material extrusion with highly filled binder-continuous feedstocks is an indirect additive-manufacturing route. Ceramic powder is compounded with a temporary polymeric or reactive vehicle, delivered as filament, pellets or granules, or a bounded binder-rich paste, and deposited as roads. Cooling, binder solidification or another declared binder-setting mechanism creates a green body; controlled debinding creates a porous intermediate; sintering develops the final ceramic microstructure. Each state has different failure modes and acceptance evidence. Powder chemistry, morphology, surface area, agglomeration and moisture interact with binder wetting, plasticisation, lubrication, solids loading and compounding. Filament systems add diameter, flexibility, stiffness, buckling and drive constraints. Pellet and screw systems add hopper flow, residence time, shear and purge. The measured rheology must be related to pressure, temperature, wall slip, particle migration and degradation in the real feed path. Deposited road width, height, overlap and interface quality depend on volumetric delivery, nozzle, stand-off, velocity, temperature history, cornering and start-stop behaviour. These variables create voids, anisotropy and dimensional bias that sintering may reduce, preserve or amplify. Debinding rate is limited by solvent, vapour and decomposition-product transport through geometry that changes as binder is removed. Sintering shrinkage is a spatial tensor affected by local solids distribution, road architecture, gravity, setter contact, phase evolution and furnace conditions. Final density alone cannot close pore topology, surface damage, interfaces or brittle reliability. This qualitative engineering review separates filament, pellet/granule and binder-continuous paste architectures, defines the boundary from direct ink writing, and provides a requirements-led qualification gate for oxide, non-oxide and functional ceramics. It excludes concrete and macroscopic construction extrusion and treats the current 3Dresyns advanced-material page only as manufacturer-declared scope.

Keywords: *ceramic material extrusion; fused filament fabrication; filament; pellet extrusion; screw extrusion; thermoplastic feedstock; green body; debinding; sintering; shrinkage; anisotropy; brittle statistics; functional ceramics; qualification*

1. Purpose, scope and terminology

ISO/ASTM 52900 defines material extrusion by selective dispensing of material through a nozzle or orifice [1]. The category identifies a delivery principle, not a feedstock chemistry, setting mechanism or final material state. In this paper, bound-ceramic material extrusion means that ceramic powder is carried in a binder-continuous feedstock and that the deposited road retains shape

primarily through cooling, binder solidification or another explicitly declared binder reaction. The intended final product is a ceramic created only after the temporary vehicle has been removed and the particles have been thermally consolidated.

The scope begins with released ceramic powder, sintering aids and every binder-system constituent. It includes storage, drying, dosing, compounding, deagglomeration, feedstock pelletisation, filament manufacture or paste preparation, packaging, ageing and reconditioning. It follows filament, pellet/granule and binder-continuous paste feeds through machine loading, transport, heating, pressurisation, nozzle flow, toolpath deposition, cooling or reaction, green-body removal, support handling, debinding, sintering, finishing, cleaning, inspection and final acceptance.

The distinction from ER-152 is mechanism-based. ER-152 controls direct ink writing and robocasting in which a particle suspension or paste forms and retains roads through yield stress, colloidal interactions, gelation, coagulation, solvent evaporation, drying or another ink-dominant mechanism. ER-154 includes a paste only when a polymeric or reactive binder is the continuous shaping phase and its cooling, solidification or declared reaction principally establishes green strength. Water content, viscosity or the supplier word paste cannot decide the boundary. The responsible route is identified by the state-forming mechanism and the downstream binder-removal chain.

ER-151 controls ceramic vat photopolymerisation. ER-153 controls liquid-binder jetting into powder beds. ER-155 controls powder-bed routes in which a polymeric binder associated with the powder is fused or otherwise consolidated to form the green geometry. ER-148 controls bound-metal material extrusion. The present paper can discuss shared powder-injection-moulding concepts because ceramic injection-moulding feedstocks can be candidates for extrusion, but it does not treat an injection-moulding feedstock as automatically printable. Gonzalez-Gutierrez and co-workers describe the broader highly filled polymer route [15], while Özden and colleagues survey ceramics made from thermoplastic feedstocks [17]. Both support the process architecture, not a universal formulation.

The delivered states are named explicitly. A released powder-binder compound is a feedstock. A filament, pellet or granule is a feed geometry, not evidence of printable behaviour. A deposited road is a green road. A completed printed object before binder removal is a green body. After partial or substantially complete removal of the binder, a fragile porous intermediate may be called a debound or brown body when that term is appropriate to the declared process. A sintered body has undergone thermal consolidation but may still require finishing, cleaning, phase verification and property testing. Only the final declared and accepted state is a ceramic product.

This review covers technical oxides, non-oxides, electroceramics and other advanced compositions at component scale. It excludes cement, concrete, geopolymer, regolith and other macroscopic construction deposition. It also excludes polymer composites that retain their polymer matrix as the final product. The temporary binder in ER-154 must be removed or transformed so that the accepted product is a declared ceramic or ceramic-dominant material.

Requirements are written for the final state before a feed architecture is selected. ISO/ASTM 52910 provides design communication principles [3], and ISO/ASTM 52901 frames purchased-part requirements and evidence [4]. A useful requirement names final composition and phase, residual porosity, surface, critical geometry, orientation, property method and environment, permissible finishing, inspection and acceptance. It also identifies whether the part is structural, thermal, electrical, dielectric, wear-resistant, chemical-service or a process demonstrator. “FFF ceramic” and “printed at high density” are not acceptance requirements.

No value in the cited literature is transferred as a production recipe. This paper does not prescribe solids loading, binder ratio, particle size, filament diameter, pellet size, drying condition, printing temperature, bed temperature, nozzle, speed, layer height, line width, flow multiplier, raster, support spacing, solvent, debinding time, heating rate, atmosphere, sintering temperature, dwell, setter, oversize factor or acceptance threshold. Every value belongs to a defined powder-binder-feed-machine-geometry-furnace-use system.

Evidence transfer is tiered. Evidence is transferable only within the demonstrated material-machine-route-state envelope. A shared process label, nominal chemistry, powder family, binder family, machine class or thermal route does not establish equivalence. Transfer outside the demonstrated envelope requires declared bridging evidence or requalification before acceptance.

2. Process identity and three feed architectures

The common chain begins when released powders and binder constituents are dosed and compounded. Mixing must distribute the particles within the continuous binder, wet their surfaces and avoid uncontrolled agglomerates, air and segregation. The compound is then converted into the selected feed geometry or loaded directly where the machine accepts compounded pellets or a binder-continuous paste. The printer meters, heats or otherwise conditions the feed, forces it through a nozzle and places successive roads. The roads cool, solidify or react, creating a green geometry whose mass, dimensions, interfaces and flaws record the entire upstream history.

The green body is a temporary composite. Ceramic particles carry most of the intended final inorganic mass, while the binder gives transport, cohesion and handleability. The body can be stiff and visually complete while still being far from the final ceramic. It must pass a green hold before debinding. Debinding removes soluble, catalytic or thermally labile fractions and then the backbone, creating connected pores through which later gases can escape. The resulting body can be too fragile for unsupported handling. Sintering then drives neck growth, densification, grain evolution and phase change. Finishing can remove support scars or establish surfaces, but it can also introduce grinding damage. Acceptance therefore belongs at the end of a controlled state chain.

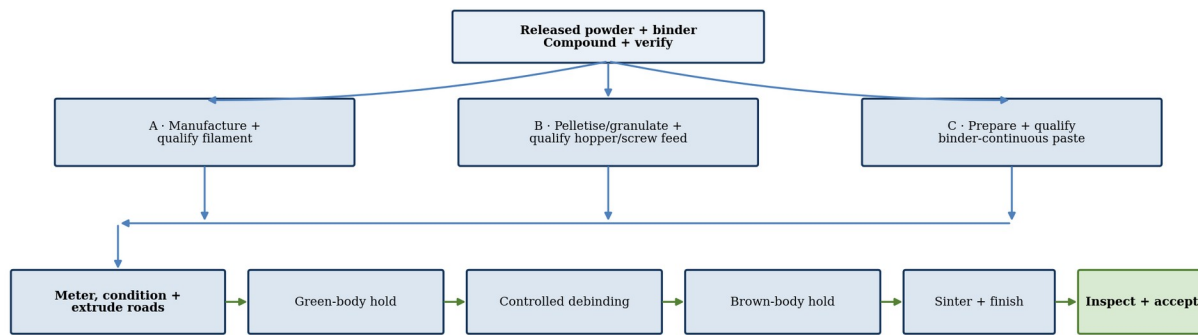
Filament feeding places a slender composite column between the drive and the hot zone. The drive must generate enough axial force to overcome nozzle resistance without stripping the surface, crushing the filament or causing it to buckle. The filament must be flexible enough to manufacture, spool, ship, unspool and route, but stiff enough in compression to transmit force. Its diameter and ovality change delivered volume and contact with guides. Its powder distribution and binder phase must remain stable around a bend and during storage. Nötzel, Eickhoff and Hanemann demonstrated small ceramic components using a highly filled filament and a low-cost printer [19], but their material and geometry establish a bounded example rather than a platform-independent capability.

Pellet or granule feeding removes the need to manufacture and mechanically route a continuous filament. A hopper supplies particles to a plunger, screw or other metering device. This can widen the feedstock design space and permit closer use of compounded injection-moulding materials. It also creates different failure modes. Granules can bridge, segregate, absorb moisture, produce inconsistent screw fill or leak through clearances. Screw speed, compression, backflow, heating zones and residence time create a melt history different from filament-fed hot ends. Start-up, interruption, colour or composition change and shutdown require purge evidence. He and co-workers provide one dense-zirconia screw-extrusion demonstration [26]; it does not prove that every pellet system is less variable or more scalable.

Binder-continuous paste feeding uses a compound that may remain soft at room temperature or set through cooling or reaction after extrusion. A syringe, cartridge, ram or screw can deliver it. This architecture can reduce filament and hopper constraints and can accept high-viscosity feedstocks, but the cartridge can contain air, settle, bleed, skin, react or develop pressure gradients. Storage time and temperature can change its extrusion response. The route belongs here only when the binder phase governs shaping and the subsequent thermal conversion resembles a bound-powder process. A colloidal ceramic ink whose stability, gelation and drying dominate the green body remains in ER-152.

Table 1. State-resolved bound-ceramic material-extrusion routes

Stage	Filament-fed route	Pellet or granule-fed route	Binder-continuous paste route	Common acceptance evidence
Material release	Compound plus filament diameter, ovality, surface and mechanical window	Compound plus granule size, moisture, flow and feeding window	Compound identity, storage, air, reaction or softening window	Powder and binder lots, solids basis, dispersion, thermal and rheological state
Machine delivery	Spool, guide, drive-wheel traction, compression and buckling	Hopper, bridging, screw/plunger fill, residence time and purge	Cartridge/ram/screw metering, pressure history and ageing	Stable mass or volume delivery without segregation or degradation
Road formation	Melting, nozzle pressure, drag, cooling and inter-road fusion	Screw/plunger melt history, pulsation, start-stop and road placement	Setting, slump, surface skin and road interaction	Measured road width, height, overlap, interfaces, seams and defects
Green state	Removal from bed, support and handling survival	Removal, support and handling survival	Set or reacted body and handling survival	Green mass, dimensions, density field, flaws and authorised debinding route
Thermal conversion	Solvent/catalytic/thermal debinding and sintering	Route-specific debinding and sintering	Declared binder removal and sintering	Brown-body integrity, mass-loss closure, atmosphere, furnace load and shrinkage
Final acceptance	Declared ceramic state and method-labelled evidence	Declared ceramic state and method-labelled evidence	Declared ceramic state and method-labelled evidence	Phase, density, geometry, pores, surface, flaws, properties and disposition



Feed-specific release risks close before the common green → brown → sintered evidence chain.

Figure 1. Three feed architectures converging on one state-resolved ceramic chain.

The branches converge only after their feed-specific delivery risks have been closed. Genealogy includes powder and additive lots, moisture and conditioning, binder lots and age, compounding equipment and order, time, temperature, torque or energy, pellet or filament production, dimensional or mechanical tests, package, storage, machine identity, feed path, software and file version, nozzle and maintenance, position and orientation, build record, green inspection, debinding load, solvent or catalyst, furnace and atmosphere, setter, thermal profile, finishing, inspection and deviation disposition. ISO/ASTM 52951 supports part-linked data packages [7], while ISO 17295 supports unambiguous position and orientation [6].

Hold points prevent visual completion from becoming premature release. Feedstock release authorises only the declared feed-manufacture or printing step. A filament or pellet batch is not authorised for use until feed behaviour is verified. A printed green body can proceed to debinding only when geometry, mass, interfaces and handling integrity are acceptable. A solvent-debound body is not authorised for rapid heating merely because its surface appears dry. A sintered body is not accepted until composition, dimensions, defects, surface and properties satisfy the final requirement.

3. Powder, binder and feedstock design

The ceramic powder establishes the final inorganic composition and much of the sintering response. Relevant attributes include identity, phase, purity, sintering aids, particle morphology, size distribution, specific surface, porosity, surface chemistry, agglomeration, moisture, adsorbed species and lot variability. Fine particles can support densification but increase surface area, binder demand, agglomeration and viscosity. Coarser particles can reduce surface-driven interactions yet change packing, feature formation and sintering. A multimodal distribution can improve packing in one system while segregating during feeding or compounding in another.

The binder is a functional system rather than an inert diluent. A low-molecular-mass or soluble fraction can reduce viscosity and create pores during early debinding. A backbone maintains shape after that fraction leaves. Plasticisers, waxes, lubricants, surfactants, dispersants, compatibilisers and stabilisers can alter wetting, particle separation, feed flexibility, wall slip, thermal stability and residue. The constituents must be compatible with powder surfaces, compounding temperatures, machine materials, storage, debinding mechanism, atmosphere and final phase. A component that improves filament bending can worsen creep, drive-wheel deformation or green slump. A surfactant that lowers viscosity can remain at an interface or change decomposition.

Solids loading is meaningful only with its basis and measurement. Mass percent depends strongly on powder density and cannot be compared directly among alumina, zirconia, barium titanate, boron carbide and silicon carbide. Volume percent relates more directly to the continuous phases but still does not prove dispersion, pore-free compounding or local uniformity. Maximum loading is not a factory objective. Raising loading can reduce binder burden and shrinkage but increase compound viscosity, pressure, particle-particle interactions, abrasion and brittleness. Lower loading can improve flow and filament flexibility while increasing binder removal, final shrinkage and the risk of distortion or residual pores.

Compounding creates the feedstock microstructure. Dosing error, addition order, premixing, rotor or screw configuration, temperature, shear, time, torque, degassing and cooling determine dispersion and degradation. A stable torque plateau can support process control but does not by itself prove that all agglomerates are broken or that no air remains. Repeated extrusion can improve distribution while accumulating thermal and shear history. The compound must be sampled across the batch and across start, middle and end discharge, not only from a convenient location.

Powder-binder wetting and dispersion should be investigated with failure hypotheses. Microscopy, density, ash content, thermogravimetry, differential scanning calorimetry, spectroscopy, rheology, torque and mechanical tests can reveal different aspects. Sections can show agglomerates or voids but may not represent the entire batch. Ash content can confirm average inorganic fraction while missing local segregation. Thermal analysis can support a debinding plan but not predict heat and mass

transport in a large part. The test plan links each measurement to a later failure and establishes release limits from qualified outcomes.

Gorjan and co-workers showed in an alumina-EVA system that stearic-acid level changed both rheological behaviour and the brittleness or flexibility of the solid filament [21]. That result illustrates a general coupling: an additive cannot be optimised against viscosity alone. The exact composition and reported values remain specific to their materials. Nötzel and Hanemann similarly developed an alumina feedstock and demonstrated the complete route [20], but the transferable lesson is the need to connect feedstock, filament, printing, debinding and sintering, not to copy their formulation.

Moisture and contamination can enter at powder opening, compounding, cooling, grinding, pelletisation, filament storage and machine loading. Hygroscopic binder components and high-surface-area powders may change during exposure. Water can plasticise, hydrolyse, volatilise or create bubbles depending on chemistry. Metal wear particles from screws, gears or nozzles can contaminate electrical or colour-sensitive ceramics. Every contact surface, cleaning agent, regrind stream and packaging material therefore belongs to the contamination assessment.

Rework requires a controlled definition. Reground filament, purge, off-specification pellets and clean start-up material may contain additional thermal history, moisture, contamination and changed particle or binder distribution. A percentage rework rule is insufficient unless the stream has identity, history, release tests and demonstrated effect on printing and final properties. Unknown floor sweepings, mixed purge and aged open-container material are not feedstock.

The development sequence should progress from material identity to compound stability, feed manufacture, delivery, road formation, green-body integrity, debinding and sintering. Travitzky and co-workers place material design and process selection together in ceramic AM [14]. Spina and Morfini summarise the filament route and its dependence on binder, printing and thermal conversion [18]. Review evidence is useful for generating risks and selecting experiments, but final acceptance must be supported by the actual controlled system.

4. Filament manufacture, mechanics and feeding

Filament production is a second extrusion process before printing. The compound is melted or softened, pressurised through a die, drawn, cooled, measured and wound. Die swell, puller speed, cooling asymmetry, gravity, residual stress and powder distribution can change diameter, ovality, curvature and surface. The centre and surface can cool at different rates, creating a structure that later relaxes on storage or reheating. A filament lot must therefore be defined by more than nominal diameter and composition. General material-extrusion machine mechanics, including filament buckling and drive traction, are inherited from ER-140; ER-154 adds the ceramic-specific consequences of high filler loading, brittleness and powder-distribution stability.

Diameter controls both machine fit and delivered volume. Local undersize can reduce drive contact or mass flow; oversize can jam a guide or hot-end entrance. Ovality makes contact and flow orientation-dependent. Short gauge measurements can miss long-wave variation, and an average can hide local excursions. Continuous or statistically representative measurement, spool mapping and traceability are preferable when delivered volume or buckling margin is narrow. Surface roughness, lubricant migration and powder exposure can change drive-wheel traction and generate debris.

The mechanical window contains competing requirements. The filament needs tensile integrity during winding and unwinding, bending compliance around the spool and guides, and compressive stiffness between the drive and the melt zone. Too brittle, it cracks or snaps. Too soft, it creeps, flattens or is carved by the drive. Too flexible under compression, it buckles when nozzle pressure rises. Too stiff in bending, it cannot be spooled or routed without fracture. Temperature and ageing shift this window, so room-condition testing alone may not represent a warm machine enclosure or cold transport.

Buckling is a system failure. Unsupported length, filament modulus, diameter, guide clearance, drive force, friction, hot-zone entrance and melt resistance all contribute. Shortening the free span can improve stability without correcting high viscosity or a blocked nozzle. Increasing drive force can postpone slip while damaging the surface or accelerating buckling. A robust qualification records the first failure mode across allowable feed and nozzle conditions and establishes monitored limits with margin.

The drive wheel can imprint, abrade or crush a highly filled filament. Tooth geometry, pinch force, alignment and debris determine how force is transmitted. Surface damage can produce particles that contaminate the guide or hot end. Repeated retractions can work the same segment and change its diameter or local temperature. The control plan includes drive condition, cleaning, tension, feed-path alignment and the consequence of skipped or ground filament.

Spool geometry and history affect feeding. Tight winding can impose curvature and residual strain. Crossed turns, flange contact and inconsistent tension can create intermittent load. A small spool radius challenges brittle material more than a large radius. Filament stored under tension can creep or develop flat regions. Packaging must control moisture, temperature, shock and time, and the opening procedure should prevent the feed from acquiring an uncontrolled environmental history.

Nötzel, Eickhoff and Hanemann connected small features to a highly filled alumina filament, nozzle and complete debind-sinter chain [19]. Their work supports the feasibility of carefully matched systems and the importance of fine-feature feed requirements. It does not justify the shortcut that a smaller nozzle always improves resolution. Pressure, agglomerate size, abrasion, road continuity, thermal gradients and drive margin can become limiting first.

Lee and co-workers studied a highly filled dual-layer polymer/ceramic filament [30]. A core-shell or coextruded design can separate some filament mechanical functions from the highly filled core, but it creates a persistent interface and an additional composition-distribution problem. Shell thickness, concentricity, adhesion, relative flow, decomposition and residue must be controlled. A filament that feeds well can still create an unacceptable ceramic if shell material redistributes, leaves carbon or changes local porosity.

Filament release combines composition, dimensions and functional feeding. Representative checks can include inorganic fraction, density, diameter distribution, ovality, surface, curvature, tensile response, bend or spool test, compressive or buckling proxy, thermal transitions, rheology and a controlled extrusion test. The release artefact should challenge the declared free span, nozzle, temperature and feed rate. A single visually successful print is not a feed qualification because it may not expose spool-end, long-build, retraction or adverse-temperature conditions.

5. Pellet, granule and binder-continuous paste architectures

Pellet or granule feed separates compound manufacture from filament manufacture. The compound is extruded, cooled and chopped or otherwise granulated, then loaded into a hopper. This can remove filament diameter, bending and buckling constraints and can permit faster screening of candidate ceramic injection-moulding compositions. It does not remove the need for a stable feed geometry. Granule size, shape, fines, surface, moisture, static charge and bulk density influence hopper discharge and screw fill.

Hopper flow must be demonstrated in the actual machine orientation and environment. A free-flowing jar test can miss arching across a narrow throat, ratholing, segregation, vibration compaction and intermittent starvation. Very large granules can bridge or fail to enter a screw channel. Excess fines can pack, dust or feed disproportionately. A broad distribution can change bulk density as the hopper empties. Level sensors and gravimetric checks can support monitoring, but they require a validated relation to delivered compound.

A screw-fed extruder creates axial transport, melting, pressure generation and mixing. Screw geometry, speed, fill, barrel zones, back pressure and nozzle resistance determine residence time and shear. The feed can experience a wide residence-time distribution, so a small fraction may degrade during slow printing, pauses or high-temperature holds. Gas, discolouration or viscosity change can appear after the average material still seems acceptable. Start-up and purge criteria must therefore be based on identity and condition, not a fixed arbitrary purge length.

Plunger or ram systems have different behaviour. They can deliver a preheated charge without screw mixing but may create pressure decay, wall slip, dead zones and batch discontinuities. A cartridge or barrel can develop temperature and composition gradients. Seals can introduce contamination or variable friction. The useful comparison is not screw versus ram in the abstract; it is whether the declared metering system maintains mass flow, feedstock state and road geometry across the qualified operating envelope.

He and colleagues demonstrated dense zirconia using screw extrusion [26]. The work supports the viability of a granule/screw architecture and highlights the need to couple feed, nozzle and thermal conversion. It cannot establish that a screw automatically homogenises the compound or removes voids. Pellet systems still depend on upstream compounding and can generate their own thermal, pressure and residence histories.

Hadian and co-workers evaluated powder-injection-moulding feedstock compositions for zirconia material extrusion [29]. The industrial opportunity is important: an established PIM or CIM compound can shorten development and connect prototypes with moulding production. The transfer remains conditional. Injection moulding uses a closed, pressurised mould and a different shear, cooling and packing field. Material extrusion produces unsupported roads, free surfaces, repeated thermal cycles and intentional interfaces. A feedstock that fills a mould may slump, separate, ooze, curl or form weak roads when printed.

Pellet-fed multi-material processing adds transition and contamination control. Two hoppers or extruders can place different ceramics or functional compositions, but each material has its own viscosity, thermal stability and shrinkage. A purge tower or discarded transition region does not prove that the accepted part has the intended composition boundary. Residence volume, backflow and wetting can create a diffuse transition. After debinding and sintering, differential shrinkage, reaction and thermal expansion can crack or delaminate the interface.

Binder-continuous paste systems require a separate state definition. The paste may be loaded into a cartridge, deaerated and metered through a syringe, ram or screw. If the road is stabilised mainly by cooling, thermoplastic solidification or a declared

binder reaction, and if the downstream chain removes that binder before sintering, the route can be controlled within ER-154. If colloidal yield stress, gelation, coagulation or drying of a suspension is the principal state-forming mechanism, ER-152 owns it.

Paste storage can change rheology and reactivity. Particle sedimentation or creaming, binder bleeding, solvent loss, skinning, crystallisation, pre-reaction and gas entrainment can produce axial gradients within a cartridge. Filling can introduce air and material interfaces. A pressure trace can identify some blockages or voids but cannot establish composition. Cartridge position, age, freeze-thaw or thermal history, deaeration and end-of-cartridge behaviour belong to qualification.

Paste extrusion can reduce the need to melt a preformed solid, but it may require a high yield stress or rapid setting to resist slump. Increasing the setting rate can reduce bead fusion or clog the nozzle. Lowering viscosity can improve flow while worsening shape retention and particle segregation. The development window therefore links storage stability, delivery pressure, road formation, inter-road bonding, green strength and binder removal. The word paste is not a material class and supplies no safe process window.

The feed-architecture decision should follow the dominant risk. Filament can suit distributed equipment and sealed, traceable feed when the mechanical window is robust. Pellets can support rapid compound iteration, larger flow or direct use of granulated feedstocks when hopper and residence control are strong. Binder-continuous paste can support compounds that cannot be made into flexible filament or free-flowing granules, provided storage and setting remain controlled. No route is universally more accurate, economical or scalable.

6. Rheology, thermal history, nozzle flow and wear

The feedstock must move through a complex path before becoming a road. It can be compressed, bent, softened, melted, sheared, elongated, depressurised and cooled. The apparent viscosity depends on temperature, shear rate, pressure, particle loading, dispersion and time. Highly filled systems are often shear thinning and can show yield behaviour or wall slip, but a model fit does not replace measurement in the relevant state. General nozzle-flow and material-extrusion process mechanics are inherited from ER-140; ER-154 retains abrasive-bore wear and highly filled ceramic-feedstock effects.

Rotational or capillary rheometry can compare compounds and support a process window. The measurement geometry, gap, surface, slip control, pre-shear, thermal history and residence time must be declared. A rotational curve at low pressure may not represent a narrow nozzle. A capillary test can better approach pressure-driven flow but can still differ in entrance geometry, wall material, heating and shear history. The result is an input to system qualification, not a direct printer setting.

Wall slip can be useful or dangerous. A lubricating binder-rich layer can reduce apparent pressure and protect the bulk from excessive shear. The same migration can create a road surface with a different composition, a weak interface or a residue gradient. Particle migration can also change solids loading along the nozzle radius or over time. Surface and bulk sampling after extrusion can test whether flow has redistributed constituents.

Temperature creates several simultaneous effects. Heating lowers viscosity and can improve fusion, but it can also degrade binder, volatilise constituents, increase oozing or change wetting. The powder and binder can have different thermal conductivity, so the feed cross-section may not be isothermal. A thermocouple in the heater block measures a machine location, not necessarily the material temperature. Residence time and start-stop history are therefore part of the thermal dose.

Nozzle pressure is not controlled by temperature alone. Feed rate, nozzle length and diameter, entrance contraction, roughness, agglomerates, solids loading, wall slip and degradation contribute. An increasing drive load or motor torque can indicate cooling, obstruction, viscosity drift or feed damage. The signal is useful only if normal variation and failure thresholds have been correlated with road and part outcomes.

Abrasion matters because ceramic particles are hard and often angular. Nozzle diameter and internal finish can change with use, altering flow and road geometry. Wear particles can contaminate the ceramic. A larger worn orifice may reduce pressure while creating apparent over-extrusion; the machine can look easier to run as control deteriorates. Nozzle material, lot, use time, cleaning, inspection and replacement criteria belong to the equipment state.

Agglomerates and foreign material can produce intermittent blockage. A feed may pass through a wide development nozzle and fail at the production nozzle. Filtering a molten highly filled compound is often impractical, so upstream powder and compounding controls must bound oversize particles. The relation between maximum agglomerate, nozzle and required road is demonstrated rather than reduced to a universal ratio.

Start-up and interruption expose unstable states. The first road can contain aged material, air or an incomplete melt. Retraction can draw air or create decompressed zones. Pauses increase residence time and cool prior roads. Restart can generate a blob, underfill or weak weld. Purge, priming and restart procedures should be qualified against composition, mass and road geometry, with discarded material included in the mass balance.

Road output is measured directly. Useful evidence includes extruded mass per commanded length, road width and height, surface, continuity, start-stop response, corner response, pressure or motor signal, and cross-section composition. Repetition should include

spool start and end, full and low hopper, long build, environmental limits, new and aged nozzle, and allowed pause. A stable average cannot close periodic pulsation or position-dependent variation.

Gorjan and co-workers linked formulation, rheology, filament mechanics and print defects in one alumina system [21]. Their work supports multi-response optimisation. Hadian and colleagues showed that large zirconia structures required attention to printing defects and a debinding plan designed for the actual binder and geometry [25]. Both studies reinforce a central rule: low apparent viscosity, successful extrusion or a visually smooth road is not sufficient evidence of a qualified ceramic process.

7. Road formation, toolpaths, interfaces and green geometry

The nozzle delivers a moving material stream onto a substrate or prior road. The deposited cross-section is created by volumetric flow, nozzle geometry, stand-off, path speed, material temperature, substrate temperature, cooling, surface energy and the mechanical interaction between nozzle and road. Commanded line width and layer height are instructions. They become physical dimensions only through measured calibration. General road, seam and toolpath-formation mechanics are inherited from ER-140; ER-154 owns their persistence into ceramic green architecture and the sintered flaw population.

Road width can increase through die swell, over-delivery, compression or low viscosity. It can decrease through under-delivery, high speed, slip or tensile drawing. Height depends on the gap and on how the road is pressed or allowed to relax. A low gap can improve contact while scraping prior material, building pressure or damaging particle distribution. A high gap can create a rounded road with poor contact. Calibration should therefore measure both width and height and the resulting overlap.

Adjacent roads need sufficient contact and interdiffusion or binder fusion to create a coherent green body. Too little overlap leaves channels or sharp notches. Too much overlap can create ridges, overfill and local solids redistribution. The time and temperature between roads affect bonding. A perimeter deposited long before infill may have a different interface from two adjacent infill roads. Cooling fans, chamber state, large cross-sections and sparse features change these histories.

Layer interfaces add a second time scale. Each new layer contacts a surface that may be warm, cool, oxidised, contaminated or geometrically rough. Insufficient remelting or binder mobility leaves a weak boundary. Excess heat can deform lower roads or promote binder migration. The interface can be nearly invisible in a polished section and still influence fracture because small elongated pores or composition gradients align with the road architecture.

Start-stop events and seams concentrate risk. Pressure build-up and decay, retraction, nozzle wipe and travel create local underfill, blobs or voids. Placing all seams on one line can create a through-thickness defect column. Randomising seams can distribute defects but complicate inspection and surface control. The strategy is selected against the final load, sealing, electrical, thermal and finishing requirements and then recorded in genealogy.

Corners and speed changes disturb flow. The motion system decelerates while material pressure may remain. Acute corners can round, bulge or lift. Small islands can receive disproportionate heat and start-stop transients. Long straight roads can accumulate different strain and cooling than short contours. Toolpath planning must therefore include pressure and thermal behaviour, not only geometric coverage.

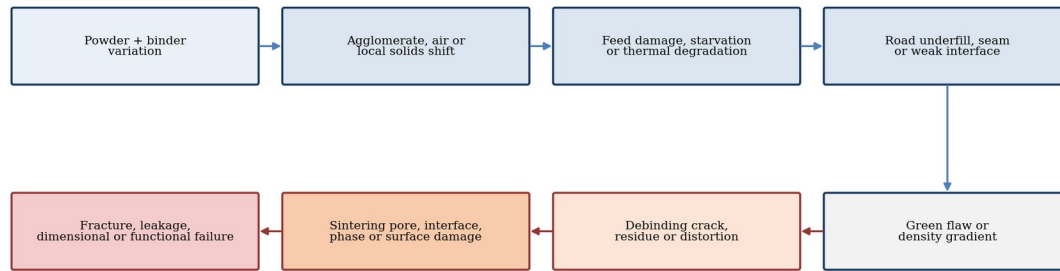
Nominal infill is not material density. A command of 100 percent can still contain road-edge voids, under-extrusion, corner gaps, seam pores and interlayer defects. A lower commanded infill can intentionally produce a porous structure, but the physical pore network depends on actual road dimensions and shrinkage. Mass, dimensions, microscopy or computed tomography can help establish the green architecture. The test method must resolve the relevant pore and feature scales.

Orientation is a material variable. Cano and co-workers demonstrated that infill orientation affected zirconia properties in their filament route [22]. The relevant inference is not a universal best raster. It is that road and layer geometry can create direction-dependent flaw populations and properties after sintering. Orientation, specimen extraction, surface and test method must be declared whenever results are compared.

Lightweight ceramics make intentional porosity and process defects difficult to separate. Orlovská and colleagues investigated fracture and mechanical properties of lightweight alumina produced by filament fabrication [23]. A designed pore architecture can be functional, while unintended road gaps, delamination or large processing voids reduce reliability. Qualification must distinguish design porosity from defect populations and measure both in the final state.

Supports are part of the manufacturing chain. A support must carry the green geometry during printing and can remain influential during debinding and sintering. Contact can scar the surface, trap binder or constrain shrinkage. A support printed from the same feed can sinter to the part if separation is poor. A second material adds chemical, debinding and differential-shrinkage risks. Unsupported bridges and overhangs are bounded by green rheology, cooling, span, road tension and later thermal distortion.

Hadian and co-workers developed design rules for alumina nozzles and heat exchangers while considering printing, debinding and sintering together [31]. This complete-chain perspective is essential. A channel that can be printed may trap binder or fail to vent. A thin wall that survives printing may warp during sintering. A support-free overhang may sag after binder softening. Design rules belong to a declared feed-machine-thermal route and require revalidation after material or geometry change.



Qualification links each final failure mode back to its earliest observable state and controlled genealogy.

Figure 2. How upstream variation becomes a final ceramic flaw.

The green body should be treated as a measurable product of the printing cell. Relevant evidence includes mass, envelope dimensions, critical features, flatness, road and seam condition, support contact, visible cracks, density or porosity proxy, internal channels and selected non-destructive or destructive sections. The measurement plan is established before qualification so that a later failure can be traced to a state, not merely observed in the final ceramic.

8. Green handling, metrology and process monitoring

Green strength must be sufficient for removal, cleaning, measurement, support handling, transport and loading into the debinding system. Maximum strength is not automatically desirable because more or stronger binder can increase debinding burden, gas generation, residue or distortion. The target is the minimum robust window that survives the declared tasks with margin.

Removal from the build surface can impose bending, peel and impact loads. A compliant polymer-style scraper procedure may crack a brittle highly filled green body. Bed adhesion that prevents warpage during printing can become excessive at removal. Cooling rate, release layer, plate condition and part orientation therefore belong to the process. Damage can be subcritical and later act as a sintering crack or fracture origin.

Handling fixtures should support the real load path. Thin walls, lattices and internal channels can deform under their own weight when the binder softens during early heating. A room-temperature green-body test cannot close that condition. Setters, wicking media, sacrificial powder or supports can stabilise geometry, but they can contaminate surfaces, restrict gas flow or constrain shrinkage. Their identity and placement are controlled.

Green metrology provides the baseline for shrinkage and defect attribution. The coordinate system follows the build and part orientation defined under ISO 17295 [6]. Critical dimensions are measured with methods that do not damage or significantly load the part. Optical scanning can capture external geometry but miss internal roads and material state. Computed tomography can resolve internal voids where contrast and voxel size are adequate, but it is not automatically representative or economical for every production part.

Mass is a high-leverage signal. Compared with a validated geometry and feedstock, it can detect major under- or over-delivery, trapped supports or material loss. Mass cannot locate the defect, distinguish composition or prove uniform density. It becomes more useful when combined with dimensions, process signals and representative internal evidence. Green mass, post-debinding mass and final mass support a state-resolved material balance.

Process monitoring should begin with a defined failure and response. Filament motion, drive load, screw torque, pressure, temperature, hopper level, motor current, machine images, layer topography and chamber conditions can each provide useful signals. None is quality by itself. A signal must have a validated acquisition chain, baseline, threshold, alarm logic and disposition. The process must specify what happens when data are missing or an excursion occurs.

Camera images can detect gross under-extrusion, displaced roads, stringing or warpage. They may miss composition, subsurface voids or a weak interface. Motor load can detect a blockage but may also respond to spool drag or temperature. Temperature data can reveal heater drift while missing material-core temperature. Data fusion can improve detection, but model training and false-negative control must reflect adverse conditions and new lots.

Orlovská and co-workers monitored critical stages in producing dense alumina parts by filament fabrication [27]. Their state-aware approach supports monitoring across printing and thermal conversion rather than a single machine dashboard. The specific sensors and limits remain tied to their system. Factory monitoring must be validated against its own feed, geometry, defects and acceptance requirements.

Green-body sampling should include build position, orientation, long and short roads, seams, thin and thick regions, channels, supported and unsupported features, beginning and end of feed, and environmental or equipment limits. Witness coupons are useful only when they share relevant thermal and flow histories. A detached cube cannot represent a large heat exchanger with enclosed channels or a tall thin shell.

Deviation control preserves information. A filament break, hopper starvation, pause, nozzle change, pressure alarm or handling chip is recorded against the part and position. Reprinting without recording the event removes evidence needed to understand systemic risk. A deviation may be dispositioned through additional inspection or rejection, but it cannot be erased by a visually successful final surface.

9. Debinding as transport, chemistry and structural risk

Debinding removes the temporary organic or reactive vehicle without losing geometry. It can use solvent, water, catalytic chemistry, thermal decomposition or a sequence of methods. Lotfizarei and co-workers review debinding routes for powder material extrusion [16]. The transferable principle is mechanism selection and state control. A published schedule is not transferable because transport length, binder chemistry, solids distribution, geometry, atmosphere, support and equipment differ. For corpus governance, ER-037 controls the generic binder-removal, gas-transport and brown-body defect architecture for binder-bearing powder-loaded green bodies; ER-154 retains route-specific feed architecture, geometry, atmosphere, setter and sintering consequences.

A multi-component binder often separates removal functions. An early soluble or catalytic fraction leaves a connected pore network while a backbone retains shape. Thermal treatment later removes the backbone and other residues. The early step must remove enough material to create transport paths without dissolving or weakening the entire skeleton. The remaining backbone must be continuous enough for handling yet accessible to later decomposition products.

Solvent or water debinding depends on solubility, diffusion, convection, temperature, agitation, part geometry and the evolving pore network. The surface can extract faster than the core, creating gradients and stress. Thick sections and enclosed volumes extend the transport path. A measured mass plateau can indicate reduced removal rate but does not automatically prove uniform extraction. Sectioning, residual analysis or model-supported evidence may be required during development.

Solvent swelling can close pores, soften supports or distort the body. Dissolved binder can redeposit during drying. Rapid drying can create skin, internal pressure or differential shrinkage. The solvent acquires binder and powder contamination and eventually requires controlled replacement or recovery. Bath volume, concentration, agitation, loading, temperature, part spacing, time, rinse and drying therefore belong to the process definition.

Catalytic debinding introduces reagent transport, reaction heat, corrosive vapours and by-products. Equipment compatibility, ventilation, neutralisation and emergency controls are process-specific. The term catalytic does not mean fast or residue-free for every geometry. A binder designed for catalytic removal can still require a thermal backbone step and careful gas transport.

Thermal debinding converts and transports binder fragments while the body is weakest. Heating softens or melts constituents before they decompose. If liquid binder migrates under gravity or capillary forces, local solids and pores change. If gas generation exceeds transport, internal pressure causes bubbles, cracks, delamination or rupture. Oxidising and inert atmospheres change decomposition and residue. Furnace flow and load arrangement can create part-to-part differences.

Thermogravimetric analysis can identify mass-loss regions under a small-sample protocol. It cannot directly set a production heating rate for a thick, enclosed part. The production part has thermal gradients and longer gas paths, and the furnace has its own transfer and flow. Kinetic analysis and modelling can support schedule design, but predictions require validation with representative geometry and load. Hadian and colleagues used kinetic analysis and combined debinding strategies in a large-zirconia study [25]; their method supports evidence-led schedule design, not schedule copying.

Geometry is part of debinding. Abrupt thickness transitions, blind cavities, low-permeability skins, dense perimeter shells, thick bosses and trapped supports can create local gas paths much longer than coupon thickness. Channel design should consider both printing access and binder/product transport. Vent features can assist removal but become final surfaces that require design and inspection.

The brown or debound body needs a controlled hold. Mass loss, dimensions, visible cracks, support condition and representative residue or internal evidence are compared with qualified limits. The body can be extremely fragile and may need to remain on a setter or in packing media. Transferring or touching it without a validated method can introduce flaws after the most informative green inspection has already passed.

Tosto and co-workers demonstrated an alumina/polymer filament route through debinding and sintering [28]. Nötzel and colleagues reported zirconia printing and thermal processing in a specified system [24]. These examples support complete-chain feasibility. They do not collapse debinding into a generic furnace step. Each material requires chemical, mass-transport and shape-stability evidence.

Debinding mass balance separates extracted binder, volatilised products, retained residue, solvent contamination, filters, traps, powder loss and rejected bodies. Emissions and condensed products can foul equipment or affect later loads. Furnace and bath maintenance therefore belong to process capability. An accepted-looking part does not justify uncontrolled accumulation within the equipment.

10. Sintering, shrinkage, distortion, phase and surface

Sintering converts a porous particle skeleton into a ceramic microstructure through neck growth, diffusion, pore evolution, grain growth and, where applicable, liquid-phase or reaction-assisted mechanisms. The driving force and kinetics depend on powder surface, particle packing, additives, green density, atmosphere, temperature and time. The printed architecture adds road interfaces, local density fields and shape constraints that conventional pressed coupons may not contain.

Shrinkage begins from the actual green structure. If solids loading or packing differs between road centre, road edge, perimeter and infill, those regions can densify differently. Voids can close, remain, move or coarsen. A low-density interface can become a pore string. A binder-rich surface created by wall slip can shrink differently from the bulk. Sintering does not guarantee that print history disappears.

Compensation therefore requires a dimensional transfer function rather than one universal scale factor. Longitudinal, transverse and build directions can differ. Curved, thin, thick, supported and enclosed features can respond differently. Gravity, friction and setter contact can restrain one surface. A single coupon-derived percentage can correct one dimension while worsening another. The compensation model is versioned with feedstock, orientation, toolpath, furnace load and finishing allowance.

Furnace loading is a process variable. Part spacing changes radiation and gas flow. A setter can react, contaminate, stick or constrain. Packing powder can support a body while creating roughness or chemical exchange. Multiple parts can shield one another or alter local vapour. Thermocouple location and furnace setpoint do not prove that every part experienced the same thermal field. Load diagrams, sensor status, atmosphere, pressure, gas flow and maintenance are recorded.

Oxide ceramics can require air, oxygen control or other declared atmospheres depending on binders, dopants and phase. Non-oxide ceramics often require inert, vacuum, carbon-controlled, nitrogen or specialised conditions. Switching atmosphere after debinding introduces a transition that must be verified. Leaks, residual oxygen, furnace furniture and binder carbon can change phase, grain growth, colour, electrical response and density.

Hammoud and co-workers showed for printed SiC filaments that debinding atmosphere, residual carbon, coarsening and anisotropy affected pressureless sintering at high temperature [34]. The important general lesson is that material remaining from the binder route can become chemically active during sintering. The reported temperature and carbon behaviour belong to their SiC system and are not a route for alumina, zirconia, barium titanate or boron carbide.

Vozárová and colleagues demonstrated a dense boron-carbide route using a newly developed filament and a controlled debind-sinter chain [32]. B4C has its own sintering difficulty, additives and high-temperature requirements. The work expands the credible material space without supporting the statement that desktop filament processing makes every refractory non-oxide economical or production-ready.

Phase and chemistry can change during sintering. Additives can react, volatilise or segregate. Binder residue can reduce an oxide or add carbon. Furnace vapour and setters can contaminate a surface. Functional ceramics can lose stoichiometry or develop secondary phases that alter dielectric, electrical, magnetic or thermal behaviour. X-ray diffraction, microscopy, chemistry and functional tests are selected against the failure hypothesis and final requirement.

Distortion can occur before significant densification if residual binder softens or gravity acts on a weak skeleton. Later, differential densification and grain growth can warp walls, ovalise holes, close channels or twist long parts. Setter design, orientation and temporary supports can reduce motion while adding constraint. A shape-stable development coupon is insufficient when production geometry contains long spans, asymmetric mass or abrupt thickness changes.

Surface condition records several stages. Nozzle roads and layer stair steps create green roughness. Support removal can tear the binder-powder composite. Debinding can open pores or leave residue. Setters and packing media can imprint or contaminate. Sintering can round edges, expose pores or create differential grain growth. Grinding, lapping or polishing can establish the required finish but may introduce subsurface cracks and residual stress. Final surface and finishing history belong to mechanical-property interpretation.

NIST identifies ceramic-AM defects, metrology and standardisation as continuing industrial needs [12]. The qualification response is state-linked measurement: green dimensions establish printing bias; debound mass and geometry establish binder-removal response; final dimensions establish shrinkage; microscopy and phase identify material evolution; mechanical or functional tests establish the delivered state. One end-point density cannot determine which state created a defect.

11. Material families, advanced ceramics and multi-material systems

Alumina is a common development material because it is available in controlled powders and has established ceramic processing and test methods. The cited alumina studies support feedstock, filament, road, debinding and sintering concepts across specific systems [20,21,23,27,28,31]. Their reported formulations, strengths and dimensions are not mutually interchangeable. Differences in grade, binder, solids basis, nozzle, specimen, surface and test method prevent a simple ranking.

Zirconia adds phase-stability, transformation and surface concerns. Cano and co-workers linked orientation to final properties in a declared zirconia route [22]. Hadian and colleagues addressed large structures and debinding [25], while Nötzel and co-workers reported another zirconia feed and process [24]. Hadian and colleagues also investigated PIM-derived compositions [29]. Together, these studies show that the same ceramic family can require different feed and processing solutions. “Zirconia filament” is not a specification.

Barium titanate demonstrates the difference between structural and functional acceptance. Bhandari and co-workers produced BaTiO₃ feedstocks and evaluated sintered properties in their system [33]. A dielectric or ferroelectric component requires phase, density, pore, electrode, frequency, field, temperature and test geometry to be declared. A dense printed body is not qualified for an electrical function merely because its powder is BaTiO₃.

Non-oxide ceramics expand high-temperature, wear, nuclear and other advanced applications, but oxygen, carbon, additives and furnace chemistry become central. The B₄C and SiC studies provide valuable primary evidence [32,34]. They must remain bounded to their powder, binder, debinding, atmosphere and sintering routes. A result from one non-oxide cannot be used to claim generic oxidation resistance, density, toughness or safety for another.

Particle-filled binder routes can also address mixed ceramics, conductive phases and graded compositions. The feedstock must maintain spatial composition through compounding, feeding, nozzle flow, deposition, debinding and sintering. Different particles can segregate or migrate. Different binder fractions can create different gas paths. Differential shrinkage and thermal expansion can create residual stress or delamination. Chemical reaction can be desired or destructive.

Core-shell and dual-layer filaments are one strategy for decoupling feed mechanics from the ceramic-rich core [30]. Multi-extruder or tool-change systems are another strategy for placing different compounds. Both introduce interfaces whose position and thickness must be measured. A visibly sharp colour boundary is not proof of compositional sharpness, phase compatibility or functional continuity after sintering.

Advanced-material selection begins with the required final function, not the availability of powder. It asks whether the powder can be dispersed at a useful loading, whether a feed architecture can transport it, whether the green geometry can be debound, whether the atmosphere can preserve or create the intended phase, and whether final defects and properties can be measured. Scarce, reactive, toxic or high-value powders add containment, recovery and contamination requirements.

The current 3Dresyns page identifies manufacturer-declared availability of nano- and micron-scale raw materials for specialised and exotic 2D/3D material development [35]. It is used here only to define commercial scope and the need for validation-led formulation. It does not establish powder composition, surface treatment, feedstock compatibility, printability, debinding, sintering, safety or final performance. Those claims require product-specific documentation and independent or controlled evidence.

Commercial feedstock can reduce development time but does not remove qualification. Composition may be proprietary, which can limit root-cause analysis and change control. The manufacturer can control internal formulation while providing authorised users with identity, lot, storage, key acceptance attributes, change notification and process constraints. Confidentiality does not justify an untraceable material.

Material substitution is a process change. Replacing a powder grade, binder component, filament supplier, pellet lot or surface treatment can change viscosity, feeding, road geometry, debinding and final properties. Equivalence requires a comparison plan across the states most sensitive to the change. A certificate showing the same nominal chemistry cannot prove equivalent surface area, agglomeration, dispersion or sintering.

Table 2. Route and material outcomes with transfer boundaries

System	Credible opportunity	Dominant controls	Evidence that must remain bounded	No-transfer warning
Filament-fed oxide ceramic	Distributed equipment, sealed feed, small to medium complex parts	Filament mechanics, diameter, drive margin, melt flow, interfaces, debinding and sintering	Alumina and zirconia studies [19-25,27-29,31]	No formulation, strength, raster or shrinkage factor is universal
Pellet/screw-fed ceramic	Rapid compound iteration, larger flow, PIM/CIM feed candidates	Hopper flow, screw fill, residence time, degradation, pulsation and purge	Screw-zirconia and PIM-feed studies [26,29]	Injection mouldability does not prove printable unsupported roads
Binder-continuous paste	Feedstocks unsuitable for filament or free-flowing granules	Storage, air, pressure, setting, slump, road fusion and binder removal	Route must be shown binder-continuous and distinct from ER-152	Paste label does not establish route or stability
Functional oxide	Dielectric, electrical, thermal or other final function	Phase, stoichiometry, pores, interfaces, electrodes and test environment	BaTiO ₃ evidence [33]	Powder identity or density alone does not qualify function
Non-oxide ceramic	High-temperature, wear and other specialised service	Oxygen/carbon balance, additives, atmosphere, residue, coarsening and phase	B ₄ C and SiC evidence [32,34]	One non-oxide route does not transfer to another
Multi-material or core-shell	Graded function, easier feed mechanics, combined properties	Composition boundary, relative flow, binder removal, reaction and differential shrinkage	Dual-layer and multi-feed architectures [30]	Visual interface or successful feeding does not prove final integrity

12. Defects, properties, brittle statistics and final acceptance

Defects should be described by state, morphology and likely origin. Feedstock defects include agglomerates, air, contamination and local solids variation. Filament defects include diameter excursions, cracks, surface damage and eccentric composition. Delivery defects include starvation, slip, buckling, degradation, pulsation and blockage. Printing defects include underfill, overfill, voids, seams, weak interfaces, road displacement and support damage. Debinding defects include swelling, delamination, residue, gas cracks and collapse. Sintering and finishing defects include persistent pores, abnormal grains, phase gradients, warpage, contamination and surface cracks.

A final pore can have several genealogies. It may begin as trapped air in compounding, a road gap, a missing feed event, an interface notch or a gas pocket during debinding. Similar appearance does not prove common cause. Fractography, sections, computed tomography and state records should be combined where failure consequence justifies it. Corrective action aimed only at the final furnace can miss an upstream origin.

Density is method-dependent. Geometric, immersion, helium, image and computed-tomography methods can address different volumes and pore classes. Relative density depends on an appropriate theoretical value for the actual final composition and phase. A high bulk density can coexist with a critical large pore or interface. Density is therefore a characteristic, not a reliability claim.

Mechanical results require specimen, orientation, surface, finishing, environment and method. ASTM C1161 provides a defined flexural-strength method for advanced ceramics [8], and ISO 14704 provides a fine-ceramic flexural method [11]. Results from different specimen sizes, fixtures or surfaces cannot be ranked without accounting for the changed stress volume and flaw population. A polished test bar does not directly represent an as-sintered channel or support scar.

Ceramic strength is statistical because failure initiates at the most critical flaw sampled by the stressed volume and surface. ASTM C1239 provides a practice for reporting uniaxial strength data and estimating Weibull parameters [9]. Sample size, censoring, confidence and population identity matter. A high mean with broad scatter can be less useful than a lower but stable population. Mixing orientations, lots or surfaces in one fitted population can conceal mechanisms.

Fractography closes the link between process and failure. ASTM C1322 provides guidance for characterising fracture origins [10]. A road-edge pore, seam, agglomerate, support scar, machining crack or inclusion suggests a different control action. Fractography should be planned into development and qualification, not reserved for catastrophic field failure.

Orientation effects should be reported even when sintering reduces visible layer contrast. Cano and colleagues reported orientation-dependent zirconia behaviour [22]. Orlovská and colleagues related lightweight alumina structure to fracture and mechanical response [23]. These studies support population- and architecture-aware qualification. Their numerical results cannot be assigned to a different feedstock, specimen or surface.

Functional acceptance adds its own failure modes. Dielectric response can depend on porosity, phase, grain, electrode and frequency. Thermal conductivity can depend on pores and interfaces. Chemical and high-temperature service can depend on residual binder-derived species and surface damage. Each function needs a controlled method, environment and ageing or durability plan where relevant. A structural flexural test does not qualify an electrical or sealing application.

Dimensional acceptance uses a declared coordinate system, datums, measurement uncertainty and conditioning. The final geometry is compared with the requirement, not with an idealised uniform-shrinkage model. Critical internal channels, wall

thickness, flatness and interface positions receive methods appropriate to their consequence. Measurement systems are qualified before process capability is calculated.

Process capability is established only after feedstock, equipment, printing, debinding, furnace load, finishing and inspection are controlled. Pooling data across different filament lots, nozzles, furnace configurations or compensation files can create a misleading distribution. The process family is stratified until equivalence is demonstrated. Deviations and rework remain linked to individual parts.

Acceptance should state what evidence travels with the part or lot. ISO/ASTM 52927 can organise principal characteristics and corresponding methods [5]. ISO/ASTM 52920 provides the production-site and process-qualification frame [2]. The final data package links material certificates and incoming results, feed manufacture and release, build record, green inspection, debinding, furnace load, finishing, final measurements, nonconformities and authorised disposition [7].

13. Economics, safety, sustainability and factory qualification

The relevant economic unit is an accepted ceramic component, not a printed green body. Cost includes powder and binder, storage, conditioning, compounding, pellet or filament production, quality checks, machine preparation, purge, printing, supports, green inspection, debinding media or catalysts, drying, furnace loading, long thermal cycles, setters, finishing, inspection, rejected parts, equipment cleaning, maintenance and waste.

Filament systems can use comparatively low-cost motion platforms, but feedstock development and production-grade filament can dominate. Pellet systems can reduce filament-making cost and support higher flow, while adding screw hardware, purge and material-transition loss. Paste systems can avoid both filament and hopper constraints but add cartridge preparation, storage and dispensing control. Capex comparisons that omit feed preparation, debinding, sintering and inspection are incomplete.

Throughput is constrained by the slowest qualified stage. A fast printer can fill a debinding or furnace queue. Furnace batching can improve utilisation while increasing waiting time and work in process. Thick parts can require long binder-removal cycles. Finishing and inspection can dominate high-precision components. The capacity model should use route-specific yield and cycle distributions rather than catalogue build rates.

Yield is state-resolved. Feedstock yield, filament or pellet yield, print yield, green-handling yield, debinding yield, sintering yield, finishing yield and final inspection yield are measured separately. Multiplying these stages shows why a visually reliable printer can still produce low accepted-part output. Scrap cost includes the value added before the state at which failure is detected.

Design can improve economics by reducing unsupported features, abrupt thickness changes, trapped binder paths, excessive finishing and unnecessary material. It can also worsen economics if a lattice increases toolpath starts, inspection difficulty or debinding risk. Design-for-AM claims are evaluated against the full ceramic chain. Hadian and colleagues' complete-chain design work supports this approach [31].

Safety begins with actual substances and tasks. Ceramic powders can become airborne during opening, dosing, mixing, grinding, cleaning and finishing. Binder constituents can cause contact or inhalation hazards. Compounding and extrusion introduce hot surfaces, pressure, rotating equipment and fumes. Debinding can use flammable or harmful solvents, water systems that become contaminated, corrosive catalysts, or thermal decomposition with vapours and gases. Furnaces add high temperature, stored heat, gases, vacuum, oxygen deficiency and combustion risks.

NIOSH frames additive-manufacturing exposure control through task and process assessment [13]. That source supports hierarchy-based controls, containment, ventilation, work practice, housekeeping and appropriate personal protection. It does not establish that every ceramic feedstock or printer has the same emissions. Each material and process requires safety data, equipment assessment and exposure control proportionate to powder, binder, solvent, atmosphere and finishing.

Filament and pellets can reduce direct powder handling at the printer if the feed is enclosed and intact. Powder exposure remains upstream during compounding and downstream during grinding or broken-part handling. A brittle filament can shed powder-containing debris. Pellet fines and hopper loading can generate dust. The label “bound powder” is therefore not a blanket low-exposure claim.

Thermal emissions depend on binder composition, temperature, oxygen, residence time and degradation. Normal extrusion and an overheated blockage can produce different emissions. Debinding intentionally removes a large organic fraction and requires capture, treatment and maintenance. Condensate and filters are waste streams. Furnace exhaust should not be inferred safe from the final ceramic composition.

Solvent and water systems require mass balance and change criteria. Reuse can reduce consumption but can accumulate binder, particles and degradation products. Distillation or recovery can add flammability and residue concerns. Waste classification follows actual composition and local requirements. No solvent is called environmentally benign solely because it is water-miscible or bio-based.

Sustainability assessment includes powder and binder production, feed conversion, failed feed, purge, print rejects, solvent, drying, long furnace cycles, supports, setters, finishing and equipment life. Material utilisation can be high at the deposition stage while energy and yield remain poor. A lower-temperature binder removal route can still be unfavourable if it takes much longer or creates more solvent waste. Comparisons need a declared functional unit and boundary.

Factory qualification proceeds from requirements to controlled evidence. It defines the final ceramic, selects a feed architecture, qualifies incoming material and feed manufacture, establishes a machine and road window, closes green inspection, validates geometry-specific debinding and furnace loads, demonstrates final dimensions, defects and properties, and then measures repeatability across lots, positions, equipment states and time. Change control preserves that evidence after qualification.

Table 3. Bound-ceramic material-extrusion qualification gate

Gate	Required evidence	Representative failure that blocks release	Authorised output
1. Final requirement	Composition, phase, geometry, surface, properties, environment, method and acceptance	Requirement is only “ceramic FFF part” or density target	Controlled product and test specification
2. Powder and binder release	Lots, identity, moisture, solids basis, dispersion risks, thermal and safety data	Uncontrolled agglomerates, moisture or binder substitution	Material authorised for compounding
3. Feed manufacture	Compounding genealogy plus filament, pellet/granule or paste-specific release evidence	Segregation, air, diameter drift, brittle filament, hopper bridging or paste ageing	Feed authorised for declared machine window
4. Delivery and road window	Mass flow, pressure/load, temperatures, road geometry, starts, seams, interfaces and monitoring	Buckling, starvation, degradation, blockage, pulsation or weak fusion	Printing window and equipment state
5. Green-body hold	Mass, dimensions, supports, channels, visible/internal flaws and handling integrity	Cracks, underfill, trapped support, deformation or untraceable pause	Green body authorised for debinding
6. Debinding hold	Mechanism, load, solvent/catalyst/atmosphere, mass loss, residue and brown integrity	Swelling, trapped binder, gas cracks, residue or collapse	Debound body authorised for sintering
7. Sintering and finishing	Furnace/load genealogy, atmosphere, setter, shrinkage field, phase and surface	Warpage, contamination, phase loss, abnormal pores or finishing damage	Final body authorised for inspection
8. Final acceptance	Dimensions, density/pore method, defects, phase, method-labelled properties, statistics and fractography	Mean-only result, mixed populations or unresolved fracture origins	Accepted component and data package
9. Production control	Capability by lot, position, machine, nozzle, load and time; deviation and change control	Pooled unstable data, missing genealogy or uncontrolled material/equipment change	Authorised repeat production

The gate is intentionally conservative. It does not require every possible test for every part, but it requires each selected control to close a defined risk. Evidence can be reduced when consequence and capability justify it, but not by replacing state-specific data with a supplier label or successful demonstration print.

14. Conclusions and research priorities

Bound-ceramic material extrusion is attractive because it can combine complex geometry, highly filled powder-binder technology and accessible deposition hardware. Its industrial difficulty lies in the complete state chain. The machine deposits a green composite, not a ceramic. Feedstock, feed geometry, delivery, road interfaces, green handling, debinding and sintering jointly create the final flaw population and dimensions.

Filament, pellet/granule and binder-continuous paste routes should remain distinct until their feed-specific risks are closed. Filament requires a narrow mechanical-rheological window and dimensional control. Pellet systems exchange filament constraints for hopper, screw, residence and purge control. Binder-continuous pastes require storage and setting evidence and a clear mechanism boundary from direct ink writing. Superficially similar roads do not make the routes equivalent.

The most important controls are state-resolved. Solids loading has an explicit basis. Rheology is linked to the real feed path. Road width, height and overlap are measured rather than inferred from the nozzle or slicer. Green bodies are inspected before defects are obscured. Debinding is designed around chemistry, transport length and representative geometry. Shrinkage is treated as a direction- and geometry-dependent field. Final properties carry specimen, orientation, surface, method and population identity.

Research should improve in-line measurement of delivered mass and composition, prediction of filament buckling and screw residence histories, monitoring of road interfaces, non-destructive green-body inspection, geometry-aware debinding models, furnace-load thermochemical measurement and dimensional compensation that remains valid across lots. Shared benchmark artefacts should include thin and thick sections, seams, channels, supports and representative thermal paths rather than only small bars.

Advanced ceramics require more, not less, discipline. Functional oxides need final functional tests. B₄C, SiC and other non-oxides need atmosphere, residual-carbon, phase and coarsening control. Multi-material systems need interface chemistry and differential-shrinkage evidence. Manufacturer breadth can identify development opportunities but cannot substitute for controlled composition and final-state qualification.

Factory adoption should proceed through one traceable chain: define the final ceramic; release powder and binder; qualify compound and feed geometry; establish delivery and road formation; inspect the green body; validate binder removal and brown-body integrity; control furnace load, shrinkage and phase; finish without introducing unacceptable damage; measure dimensions, flaws and method-labelled properties; then authorise repeat production under genealogy, deviation and change control. Only that complete chain converts a printed green shape into an accepted ceramic component.

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