

Bound-Metal Material Extrusion: Filament and Pellet Feedstocks, Green-Part Anisotropy, Debinding, Sintering and Qualification

Compound Homogeneity, Bead Interfaces, Feed-System Control and State-Resolved Evidence

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Statement of Significance

Bound-metal material extrusion can use comparatively accessible motion and extrusion hardware to shape metal-rich green parts without a laser, electron beam or loose powder bed at the printer. That apparent simplicity moves rather than removes manufacturing difficulty. Metal powder must be compounded into a binder system that flows through a particular feed path, retains bead geometry, bonds across roads and layers, survives handling, releases binder without internal damage and densifies without unacceptable chemistry change or distortion. Filament feed adds diameter, ovality, flexibility, brittleness, winding and drive-traction constraints; pellet-, rod-, piston- and screw-fed systems add segregation, residence-time, pressure, purge and metering constraints. Nominal slicer infill is not green density, and successful extrusion is not final metal. This review defines the process as a complete indirect chain from released powder, binder and equipment to an accepted component. It shows why green anisotropy can persist through sintering, why support and setter functions must be separated, and why printer price or desktop scale cannot substitute for complete-cell qualification.

Abstract

Bound-metal material extrusion deposits a thermoplastic or otherwise flowable metal-powder/binder compound as adjacent roads and successive layers, producing a green composite that is subsequently debound and sintered or otherwise densified. Filament-fed variants can use familiar FFF-style equipment but require a compound that is both highly filled and mechanically transportable as a stable filament. Pellet-, rod-, piston- or screw-fed variants can bypass filament manufacture and process feedstocks closer to powder-injection-moulding compounds, while introducing distinct dosing, residence-time, segregation and pressure-control burdens. In either route, compound homogeneity, binder rheology, powder surface state, extrusion temperature, flow, nozzle condition, road geometry, contour/infill strategy, cooling and build orientation define a spatial green architecture. Voids at bead and layer interfaces may persist, evolve or align with critical loading after debinding and sintering. Binder removal is a mass-transport and chemistry transformation; water, solvent, catalytic and thermal steps are not interchangeable. Sintering changes dimensions, pores, chemistry and microstructure under gravity and setter interaction, so shrinkage cannot be qualified by one scale factor. This qualitative engineering review maps filament and direct-feed routes, conditional advantages, material windows, complete-cell economics, safety and part-linked evidence. It provides no transferable compound, printing, debinding, sintering, compensation or acceptance recipe.

Keywords: *bound-metal material extrusion; metal FFF; fused filament fabrication; pellet extrusion; green part; anisotropy; debinding; sintering; shrinkage; qualification*

1. Purpose and scope

ISO/ASTM 52900 defines material extrusion as an additive-manufacturing category in which material is selectively dispensed through a nozzle or orifice [1]. ER-148 addresses the indirect metal subset in which the dispensed material is a metal-powder/binder composite and the deposited object is a green body. The metal service state is created only after binder removal, sintering or another declared densification route, cooling, finishing and inspection.

The scope includes powder and binder receipt, compounding, pelletising, optional filament extrusion and spooling, feedstock storage and conditioning, filament- or pellet/rod/piston/screw-fed delivery, melt transport, nozzle extrusion, bead deposition, cooling, green support and interface strategy, part removal, green handling, solvent/water/catalytic/thermal binder removal where specified, brown-state control, sintering, setters, dimensional compensation, optional HIP or heat treatment, machining, cleaning, inspection, production economics, safety and qualification.

The process-selection gate follows ER-139, and the distinction between direct and indirect manufacturing follows ER-049 [35,36]. ER-140 owns generic polymer melt transport, feed-system operation and bead formation; ER-144 owns non-molten paste/cartridge deposition mechanics [37,38]. ER-148 inherits those upstream mechanisms and owns the consequences specific to sacrificial-carrier, highly filled metal compounds: abrasive feed-path wear, road/interface contact architecture, debinding transport and the rule that every deposition decision is also a debinding and sintering decision.

ISO/ASTM 52903-1 and 52903-2 address feedstock and equipment for material extrusion of plastic materials [3,4]. They are relevant only to generic aspects of the polymeric carrier and extrusion subsystem. They do not qualify a powder-filled metal compound, debinding route, sintered metal or complete production cell. ISO/ASTM 52920 supplies the broader site and process framework [2].

Metal binder jetting is assigned to ER-147: it deposits liquid binder into a powder bed rather than extruding a pre-compounded road. Lithography-based metal manufacturing is assigned to ER-149: it shapes a photoactive metal-filled resin or suspension.

Polymer-binder powder-bed shaping belongs to ER-155, and bound-ceramic extrusion to ER-154. Laser/electron-beam PBF and DED/WAAM belong to ER-145, ER-146 and ER-150. Conventional MIM remains a comparator and potential feedstock heritage, not an additive category owned by this paper.

This review does not prescribe powder size or shape, solids loading, binder composition, filament diameter, pellet size, moisture, extrusion temperature, pressure, speed, nozzle diameter, layer height, raster, infill, support gap, debinding medium, furnace atmosphere, thermal ramp, peak temperature, hold, shrink factor, setter material, HIP cycle or acceptance limit. Those values belong to a specified powder–binder–feedstock–extruder–geometry–thermal-route–intended-use state. Published settings are evidence for their studied systems, not transferable instructions.

2. Process identity and the state-resolved production chain

The route is sometimes described as “print, wash and sinter.” That phrase hides a sequence of material identities. Powder and polymer/additives become a compound whose homogeneity and rheology must be verified. A filament route then adds an intermediate manufacturing operation: pellet or strand extrusion, cooling, dimensional control, winding and later unwinding. A direct-feed route retains pellets, rods or bulk compound but must meter and pressurise them at the printer. Both create extruded roads whose interfaces become part of a porous green architecture.

Table 1. State-resolved bound-metal material-extrusion chain

Stage	Controlled state	Principal evidence	Invalid shortcut
Powder/binder release	Metal lot, surface/chemistry, binder/additives, storage and sampling	Certificates plus verified identity and specified tests	“Correct alloy and binder”
Compound release	Solids distribution, wetting, segregation, rheology, moisture and thermal history	Controlled compounding record and representative tests	“MIM-grade feedstock”
Filament or direct-feed release	Filament geometry/mechanics/spool or pellet/rod homogeneity and flow	Route-specific dimensional, handling and feed evidence	“Material loads”
Melt transport and deposition	Feed force/pressure, temperature, residence, nozzle state, flow, road and layer contact	Released equipment/build definition and registered process evidence	“Extruder moved”
Green-body release	Density/void architecture, dimensions, support removal, strength and damage	State-specific inspection and handling qualification	“100% infill”
Debinding/brown state	Selective binder removal, transport paths, residue, chemistry, cracks and strength	Route-specific mass/gas/thermal evidence and hold point	“Washed” or “binder gone”
Sintering/densification	Atmosphere, load, pore evolution, chemistry, shrinkage, distortion and setter contact	Furnace/load record plus mapped material/geometry evidence	“Standard MIM cycle”
Delivered acceptance	Final state, surface, cleanliness, dimensions, pores, chemistry and properties	Part-linked tests, uncertainty, genealogy and disposition	“Coupon or density passed”

The chain makes the word “feedstock” state-dependent. Metal powder is feedstock to compounding; compounded pellets may be feedstock to filament production; filament or pellets are feedstock to the printer; the green body is input to debinding. Sampling and release criteria must name the state. A powder certificate cannot establish filament flexibility, and a filament diameter check cannot establish compound homogeneity or sintered chemistry.



Figure 1. State-resolved bound-metal material-extrusion route.

One print job may use multiple spools or pellet batches; one thermal load may combine parts from multiple jobs; external debinding/sintering may cross an organisational boundary. Traceability therefore links powder and binder lots, compound batch, filament/pellet identity, equipment and nozzle, build file and location, green handling, debinding/sintering load and position, setter, post-processing, tests and final serial/batch. ISO/ASTM 52951 and 52953 provide data-package and monitoring-registration architecture, but the manufacturer must define these state transitions [9,10].

The route is indirect even when a vendor supplies a turnkey feedstock and outsourced furnace service. Outsourcing changes custody and evidence interfaces; it does not remove debinding and sintering from the product definition. ISO/ASTM 52901 requires customer/provider exchange on feedstock, final characteristics, inspection and acceptance for purchased AM parts [7]. A conforming purchase order should identify the delivered material state rather than merely the printer process name.

3. Powder–binder compound architecture and release

The compound must carry a large fraction of dense particles while flowing reproducibly through mixing, feedstock manufacture and the printhead. Powder chemistry, morphology, size distribution, surface oxide/adsorbates and packing interact

with binder wetting and melt rheology. ISO/ASTM 52907 offers metal-powder characterisation methods [12]; it does not define compoundability or one bound-metal specification.

Binder systems can include a structural backbone, a lower-molecular-mass removable fraction, plasticisers, waxes, surfactants or other additives. Their functions change across the chain. During compounding they promote wetting and dispersion. During filament handling they influence stiffness, toughness and creep. During extrusion they control flow, pressure and shape retention. During debinding they establish removal pathways and residue. A material substitution that appears minor in the printer can alter chemistry or cracking in the furnace.

Solids loading is a coupled choice. Increasing the metal fraction can reduce the organic mass to remove and the void volume that must close during sintering. It also raises melt viscosity and torque, can make filament brittle, amplify particle–particle interaction, impair layer contact and narrow processing margins. Lower loading may improve flow and filament handling while increasing binder burden, contraction and the opportunity for segregation. Eickhoff et al. investigated such coupling for Ti-6Al-4V compounds and compared filament and pellet-fed deposition in a defined route [21]. Their formulation and numerical conditions are not portable.

Homogeneity is spatial and multiscale. A bulk composition may be correct while powder-rich or binder-rich zones, agglomerates, air, contamination or thermal degradation remain. Compounding torque or melt-flow data are process indicators, not complete proof. Representative sampling, microscopy or validated compositional measures must cover batch position and the subsequent pellet/filament transformation.

Powder shape is not assigned a universal optimum. Spherical particles may improve packing or flow in some highly filled compounds, while irregular or high-surface-area particles can change viscosity, binder demand and sintering. Karimi et al. developed a nickel MEX feedstock using spiky carbonyl powder and followed it through debinding and sintering [30]. That study demonstrates a viable material-specific design, not a general advantage for spiky powder.

Moisture, oxidation and thermal history accumulate. Drying can be required for a hygroscopic binder yet can oxidise or age a sensitive compound if uncontrolled. Repeated heat during compounding, pelletising, filament extrusion, printer residence and rework can change molecular weight or additive distribution. The release record therefore limits and traces reprocessing rather than assuming unused-looking pellets or filament offcuts are virgin equivalent.

Segregation risk differs from loose-powder spreading but does not disappear. Density differences, incomplete wetting, pellet fracture, fines, vibration, hopper flow and purge can shift local composition. A printed bead that extrudes smoothly can still carry a composition or binder distribution outside the qualified state. Compound release must therefore include the largest relevant particle/agglomerate population and connect that distribution, through the actual feed path and orifice, to green structure and final chemistry.

4. Filament feedstock: manufacture, mechanics and handling

Filament is both material and a flexible mechanical transmission element. It must remain dimensionally consistent enough for the drive and melt system, stiff enough to push without buckling, tough enough to bend through the intended spool radius and guide path, and strong enough to survive traction without fracture or grinding. These demands can conflict with high powder loading and binder choices made for debinding.

Filament manufacture adds its own extrusion and cooling history. Strand diameter and ovality depend on compound flow, die, pull speed, cooling and winding tension. Particle/binder segregation, internal voids or surface cracks created here enter every printed road. A printer's volumetric command generally assumes a known incoming cross-section; local diameter variation can become under- or over-extrusion even if the feeder steps are accurate.

Spooling can store residual curvature and stress. Tight radii, ageing, temperature and humidity can change brittleness or feeding. A filament that passes a short bench bend may fail during a long build at a spool transition or guide path. Release therefore covers spool identity, winding, joints, end condition, storage, conditioning and remaining-life criteria—not merely alloy and nominal diameter.

Drive rollers or gears create traction and local compression. Excess force can notch, flatten or pulverise a filled filament; insufficient force can slip. Bowden-like paths add friction and compression length, while direct drives reduce path length but add moving mass and local heat. Tosto et al. examined two commercial metal/polymer filaments and found incomplete raster bonding and voids that remained relevant after sintering [17]. Familiar FFF hardware does not guarantee polymer-like feed behaviour or a void-free metal state.

Godec et al. showed that extrusion temperature, flow multiplier and layer thickness affected green tensile response in a studied 17-4 PH compound [16]. The valid lesson is to qualify interacting feed and deposition variables against the green state. Their optimum does not define another filament, machine or final part, and their green-strength result is not a final-metal property.

Filament changeover includes purge and identification. Residual compound in a hot end can contaminate a new alloy or binder, while an aggressive purge can expose material or overheat residue. The work instruction identifies compatible purge material, waste, nozzle/hot-end cleaning and evidence that the new state is established. Colour or spool label alone cannot clear cross-contamination.

Filament can lower the routine need to handle free metal powder at the printer, but it does not establish “powder-free” manufacture. Powder exists during compound production; damaged filament, grinding debris, purge, green machining, debinding residue and final finishing can expose particles. Safety and cleanliness remain task-specific.

5. Pellet, rod, piston and screw feeding

Direct-feed architectures can eliminate the need to transform every compound into a mechanically robust spool. Pellets or rods may be closer to established powder-injection-moulding feedstock forms and can widen the usable rheology or solids-loading space. Waalkes et al. demonstrated piston-based processing of a Ti-6Al-4V MIM feedstock in their developed system [20]. This supports the architectural distinction; their thresholds are not general settings.

Pellet feeding introduces hopper and metering behaviour. Pellet size and shape, fines, bridging, segregation, moisture and bulk density affect delivery. A screw adds channel fill, compression, shear heating, mixing, leakage and residence-time distribution. A piston adds barrel fill, wall friction, compressibility, pressure evolution and end-of-charge behaviour. A rod adds geometry, feed force and joint/continuity controls. These systems cannot be grouped as “filamentless” and assumed equivalent.

Residence time matters because binder can degrade or separate while heated. Stops, speed changes, small flow rates and restart sequences expose portions of compound to different thermal histories. A nozzle purge can show flow without proving that the material reaching the part has the correct composition or viscosity. Process monitoring should include the variables needed to reconstruct this history for the actual machine.

Pressure and motor signals can indicate restriction or feed change, but they mix causes: temperature, viscosity, packing, nozzle contamination, pellet delivery, geometry and wear. A stable average signal can coexist with pulsation or local underfill. Calibration and diagnostic tests must link signals to measured bead and green outcomes.

Direct feed can simplify supply chains when an existing qualified compound is compatible, yet it can complicate cleaning between alloys/binders. Screws, barrels, dead volumes, hoppers and seals retain material. Purging, dismantling and verification add downtime and exposure. Complete-cell economics therefore compare avoided filament manufacture with feed-system maintenance and changeover.

Eickhoff et al. found pellet-fed deposition promising relative to filament in aspects of their Ti-6Al-4V study [21]. That is not a universal pellet advantage. The correct choice follows from compound rheology, required dose stability, geometry, changeover, equipment capability, green quality, thermal route and production volume.

6. Melt transport, bead formation and layer bonding

The extrusion system softens or melts the binder phase and pressurises the particle-filled compound through a nozzle. The metal does not melt in the printer. Temperature, shear and residence change viscosity; particle loading and surface state influence slip and pressure; the nozzle and deposited environment influence road geometry. “Extrusion temperature” is therefore a spatial equipment/material condition, not a single portable number.

The flow path must also pass the largest relevant particle or agglomerate population without progressive filtration. A qualitative orifice-to-largest-particle/agglomerate constraint therefore belongs to compound release, nozzle selection and monitoring. If larger constituents accumulate upstream, the delivered road can drift in solids loading and binder fraction before full jamming occurs; if the margin is inadequate, blockage can be abrupt. Minimum road and feature size are consequently bounded by the qualified particle/agglomerate distribution through the actual orifice, not by nominal nozzle diameter alone.

Flow commands translate imperfectly into deposited volume. Filament cross-section, drive slip and melt compressibility affect filament systems. Pellet metering, screw/piston dynamics and pressure affect direct-feed systems. Nozzle wear or partial blockage changes the outlet. The process plan establishes how commands are calibrated to mass or geometry and how drift is detected.

A road must contact the prior road or layer while retaining enough shape. Too little material or poor wetting leaves gaps and weak interfaces. Excess material can overfill, smear, disturb contours or accumulate at direction changes. Cooling that is too rapid may reduce bonding; excessive retained heat can cause slump, corner growth or dimensional drift. These trade-offs belong to the compound, geometry, machine and thermal environment.

Starts, stops, retractions and seams create local states unlike steady straight deposition. Pressure must build and decay, particles/binder can respond differently, and a repeated seam can form a vertical defect path or bulge. Contour-infill junctions and small islands have different timing and contact. A qualification artefact must include these features rather than relying on long, steady roads.

Layer height, road width, nozzle size, raster, contour count, overlap and build orientation define the green mesostructure. A slicer’s nominal “100% infill” describes a toolpath intention, not a measured solid or powder fraction. Tosto et al. observed FFF-like raster voids in tested hybrid filaments [17], while Gabilondo et al. measured orientation, chamber-temperature and infill-pattern effects in one 316L bound-metal system [25]. Neither supplies a universal toolpath.

The build platform and chamber condition affect first-layer adhesion, cooling, warpage and accumulated heat. Strong adhesion can prevent green lift while making removal damage more likely. A heated chamber can improve consistency for one binder and accelerate creep or degradation for another. Surface preparation and release method are therefore qualified with the green part and support architecture.

Nozzle and feed-path wear can add contamination or alter flow, especially with abrasive filled compounds. Inspection frequency depends on material, run time, pressure, geometry and measured drift. A nominal nozzle diameter after a maintenance interval is not evidence that all intervening roads were conforming. Change control includes nozzle material, geometry and supplier as well as size.

7. Green architecture, anisotropy, supports and handling

The green body is a bonded network of powder-filled roads. It may contain intraroad porosity, gaps between roads, interlayer interfaces, contour/infill discontinuities, seams, support contacts and local binder-rich or powder-rich zones. Bulk green density cannot describe all of these. Spatial architecture matters because debinding gases and solvents use the pore network and because sintering transforms rather than automatically erases aligned defects.

A mechanism consistent with highly filled compound rheology and the observed persistence of raster defects is reduced interfacial contact formation. High powder loading leaves less mobile polymer available for chain interdiffusion, while particle interactions raise apparent yield stress and slow welding between deposited layers [17,34]. Inter-road and interlayer planes can therefore begin with lower particle-to-particle contact density than an intraroad region. Because sintering necks form at contacts, such a plane may persist after binder removal as a reduced-neck-density, reduced-load-bearing interface rather than disappearing merely because bulk density rises. The mechanism is conditional on compound, thermal history and toolpath and must be tested rather than assumed.

Build orientation changes the relationship between roads/interfaces, gravity, support, surface staircase and later service loads. Mancina et al. linked orientation and printing speed to surface, micro/macro defects and mechanical response in a studied 17-4 PH BMD route [27]. Shima et al. used X-ray CT to identify aligned printing defects associated with premature fracture along a studied build direction [29]. These findings justify orientation-specific evidence; they do not define one universally strongest orientation.

Green strength supports platform removal, support separation, cleaning, inspection, storage, transfer and furnace loading. It can be tensile, flexural, impact or contact-task specific. A strong coupon in one loading direction may still chip at a support interface or crack under its own weight. Green repair, adhesive use or surface smoothing changes the binder and thermal state and is prohibited unless separately qualified.

Print supports, separation interfaces and furnace setters must be distinguished. A printed support can resist green overhangs and warpage. A deliberately weak or dissimilar interface can enable separation. Both may be removed before debinding. A setter supports a shrinking, softening body in the furnace and can constrain motion or transfer contamination. One element may serve more than one purpose only after the combined interactions are validated.

Support removal can damage low-strength surfaces or leave residue. Removing too early can distort the part; removing after a pre-debinding step can encounter a more brittle state. Support access, tools, force direction, debris control and inspection belong to design. “Soluble” or automatically separated support does not prove a clean, dimensionally acceptable interface.

Geometric printability is not enough. Parenti et al. developed a printability assessment for tested 17-4 PH gyroids [26]. A lattice that deposits successfully must still permit binder removal, avoid trapped decomposition products, survive sintering, release from setters, meet pore/strut geometry and be inspectable. The process gate follows the feature through every state.

The green release record includes identity, mass or density evidence where validated, dimensions, surface/interface condition, support-removal result, visible damage, orientation, handling history and fitness for debinding. It intentionally does not predict final density or properties.

8. Debinding and brown-state control

Debinding removes part or all of the temporary organic system while preserving a porous powder skeleton. The operation is governed by heat and mass transport, binder chemistry, green pore architecture, section thickness, geometry, support/setter contact, load arrangement, atmosphere and exhaust. A method qualified on a thin open coupon may fail in a thick wall, enclosed cavity or lattice node.

Binder systems can use a removable fraction to create open pathways before the structural backbone is thermally removed. The first step may use water, an organic solvent, a catalyst or another specified mechanism. The terms describe the removal environment, not universal safety or completeness. Residual backbone and possibly residual removable fraction remain until verified; swelling, extraction gradients, cracking, contamination or geometry change can occur.

Eickhoff et al. developed a partially water-soluble Ti-6Al-4V feedstock and evaluated its staged route [22]. The evidence supports the feasibility of that binder architecture under its studied conditions. It does not make every component water-debindable, establish that all binder is water-soluble or justify “safe,” “non-toxic” or “biocompatible.” Water quality, temperature, agitation, time, part geometry, waste and residual binder remain controlled variables.

Thermal debinding decomposes or volatilises organic components. Gas generation must be matched to open transport paths and furnace removal. Heating too rapidly for the component’s permeability can build internal pressure, causing cracks, blisters or delamination. Prolonged or poorly controlled exposure can leave carbonaceous residue, oxidise powder, weaken a brown body or contaminate the furnace. A thermogravimetric curve or supplier recipe is a development input, not automatic release for a production geometry.

Integrated debinding and sintering can reduce transfers and cycle interfaces, but it does not collapse the transformations. Jiang et al. reported that one-step thermal debinding/sintering in their studied 17-4 PH route was prone to oxidation and non-shrinkage defects [28]. This finding requires an evidence hold point inside or around an integrated cycle; it does not prove every integrated programme unacceptable.

Compound and print architecture influence removal. Binder-rich zones generate more products; aligned bead gaps may promote transport in one direction while a dense contour impedes it. Support contact and setter coverage can restrict access. A

debinding plan therefore uses representative maximum section, enclosed paths, orientation and load rather than a small generic coupon.

The brown body can be weaker than the green body after the polymer backbone is removed and before metal necks mature. Transfers between equipment, setter adjustments or inspection can create damage. Even without a physical transfer, a validated brown-state criterion may be based on mass change, evolved-gas response, thermal record, witness evidence, residual chemistry or another route-specific measurement.

Furnace exhaust, condensate, filters and surfaces accumulate process products. Binder batch or load-family changes can alter what is released. Maintenance and cleaning are part of qualification and safety, not utilities outside the process. A completed timer or visually clean exterior cannot establish binder removal.

9. Sintering, shrinkage, setters and dimensional compensation

Sintering forms metallurgical bonds and reduces pore volume through temperature- and time-dependent transport. Powder chemistry and surface state, green density, binder residue, atmosphere, thermal profile, geometry, load position and setter interaction affect densification, grain/phase evolution, dimensions and properties. The process begins from an extruded green architecture, not from a uniform moulded continuum.

Thompson et al. followed a 316L FFF route through debinding and sintering [14], and Singh et al. analysed a 17-4 PH MIM-derived feedstock through extrusion, debinding and sintering [18]. Their results demonstrate complete-route feasibility for defined systems. They do not authorise another compound, alloy, printer or furnace recipe. Sadaf et al. likewise reported one 316L route whose state-specific results remain bounded to its materials and conditions [19].

Shrinkage closes part of the space occupied by binder and green porosity, but it is not simply proportional to nominal binder fraction. Local powder packing, road overlap, interface voids, contour/infill architecture, orientation, debinding path, gravity, setter friction and furnace field can produce anisotropic or local contraction. A global oversize factor may be a starting model; it is not a qualification result.

Gravity acts while the structure loses stiffness and densifies. A setter can support a broad surface or vulnerable span, but it can restrain sliding, mark or contaminate a surface, alter gas/heat access or over-constrain contraction. Sacrificial ribs and machining stock add material and furnace burden. The support strategy is validated from green placement through final removal and inspection.

Compensation models may include axis factors, local feature offsets, anticipated sag, setter contact and final machining stock. They are trained on representative parts and build/furnace locations, then tested on independent geometry. A model fitted and judged on the same artefacts cannot establish predictive capability. Powder, compound, nozzle, toolpath, debinding, furnace or setter changes can invalidate it.

Pressureless sintering, HIP after sintering and heat treatment produce different states. HIP can reduce some internal porosity when conditions and pore closure permit, while not necessarily correcting dimensional errors, surface-connected defects or chemistry. Singh et al. examined factors affecting Ti-6Al-4V properties across a specific metal-FFF route [24]; Zhang et al. likewise studied Ti-6Al-4V structures through their process [23]. Each property belongs to its exact densification and post-process state.

The furnace is a production asset with load-dependent usable volume, sensor/control state, atmosphere flow, setters and contamination history. A successful empty calibration or one centre coupon does not prove a dense production load uniform. Job and furnace-load genealogy must remain linked so a thermal excursion can be dispositioned at the correct population.

Dimensional acceptance names the state. Green dimensions diagnose deposition. Brown dimensions can diagnose binder-removal change. As-sintered dimensions include thermal contraction. HIPed, heat-treated, machined and delivered dimensions include further operations. A drawing and report that omit the state make comparison and compensation ambiguous.

10. Material windows, pore state, microstructure and properties

Bound-metal MEX has been demonstrated for stainless steels [14–19,25–29], titanium alloys [20–24], nickel [30], hardmetals/cermets [31] and a tungsten-heavy-alloy system [32]. This breadth shows that the platform concept is adaptable. It does not mean “any metal” can be compounded, extruded, debound and sintered. Powder–binder interaction, viscosity, oxidation, carbon pickup, sintering mechanism, phase stability and furnace compatibility remain material-specific.

Stainless-steel studies illustrate both feasibility and persistent process signatures. Gong et al. compared a 316L FDM-based route with an SLM-based route and observed route-specific porosity and properties [15]. Tosto et al. observed incomplete raster bonding and orientation dependence in tested commercial hybrid filaments [17]. Shima et al. connected CT-visible aligned printing defects to anisotropic tensile response in a 17-4 PH BMD system [29]. None supports a universal property discount or equivalence to wrought, MIM or PBF material.

Density is necessary for many applications but not sufficient. Intra-road packing defects must be distinguished from inter-road and interlayer contact-density defects. The latter can form reduced-neck-density planes even when an average section appears dense; contour-linked, surface-connected or isolated pores add other failure modes [17,34]. Their shape, orientation and location affect load-bearing area, leak, fatigue and corrosion. A high bulk relative density can coexist with a critical aligned defect. Test method, surface condition and state must accompany every density value.

Microstructure and chemistry reflect the complete route. Binder-derived carbon, powder oxide, debinding atmosphere, sintering atmosphere, time/temperature and cooling can affect phases, inclusions, grain size and precipitates. A heat treatment can change strength and phase without erasing print-aligned defects. Shima et al. explicitly separated as-sintered microstructure from a subsequent solution-and-ageing state [29]; property claims must do the same.

Titanium alloys tighten chemistry control because oxygen and carbon changes can matter to the intended property and application. Eickhoff et al. followed compounding, FFF/pellet deposition, debinding, sintering and optional densification in a tested Ti-6Al-4V route [21], while Singh et al. examined property factors in another [24]. The permitted inference is that chemistry and densification must be measured after the complete route—not that a universal titanium binder or atmosphere exists.

Nickel, hardmetal/cermet and tungsten-heavy-alloy studies expand the evidence boundary. Karimi et al. created a nickel feedstock around a particular powder and binder [30]. Lengauer et al. examined extrusion-based hardmetal/cermet components [31], and Bose et al. studied one tungsten-heavy-alloy route [32]. These are material-specific demonstrations. They do not establish that a raw powder portfolio is already a printable feedstock.

Mechanical tests must represent orientation, geometry, surface, heat treatment and intended failure mode. ISO/ASTM 52927 structures characteristics and corresponding test agreements [8]. A machined tensile bar can remove the as-sintered surface and sample a simpler stress state than the component. Coupon evidence must have a validated relationship to the delivered part.

The 3Dresyns nano/micron page lists metal, alloy and other advanced raw-material families and places them in direct/indirect manufacturing context [33]. ER-148 uses that page only for scope. It does not establish compound homogeneity, filament or pellet behaviour, printability, debinding, sintering, chemistry, safety or final performance. Each proposed material requires independent powder–binder–extrusion–thermal–part qualification.

Table 2. Conditional opportunities and controlling liabilities in bound-metal material extrusion

Process or product condition	Conditional opportunity	Controlling liability	Evidence required
Filament-fed printer	Familiar, compact feed and motion architecture can lower entry complexity	Filament manufacture, brittleness, geometry, traction and spool ageing constrain feed	Spool-to-bead-to-final-state correlation
Pellet/direct feed	Can bypass filament mechanics and use a wider compound form	Hopper/screw/piston metering, residence, purge and segregation burdens	Mass/pressure/residence and green-uniformity evidence
No loose powder bed at printer	Can reduce some routine powder-spreading and recovery tasks	Powder exists in compounding; debris, purge, off-gas, furnace and finishing remain	Task-specific exposure and containment assessment
Low printer heat input	Avoids a metal melt pool during shaping	Polymer road interfaces and large later thermal transformation remain	Green architecture and final defect/property evidence
Toolpath flexibility	Raster, contour and local deposition can tailor green geometry	Seams, interfaces, starts/stops and orientation create anisotropic defects	Representative geometry and registered toolpath evidence
Separable green supports	Support/interface can aid printing and pre-furnace removal	Removal damage and sintering setter/sag needs remain	State-specific support, setter and surface qualification
MIM-feedstock heritage	Established compounding and thermal knowledge can accelerate development	FFF/direct-feed rheology, bead interfaces and geometry differ from mould filling	Route-specific extrusion, debinding and final-part validation
Advanced or dense alloy powder	Indirect shaping can avoid some melt-pool constraints	Viscosity, filament/feed integrity, oxidation, residue and sintering remain alloy-specific	Complete material and furnace window

The table makes cost and safety claims conditional. An inexpensive printer can feed an expensive or difficult thermal cell. A contained spool can reduce one powder task while adding filament manufacturing and purge. A MIM-derived compound can bring useful heritage while encountering bead interfaces that injection moulding does not create. The best use case is the one whose complete route closes, not the one with the simplest printer demonstration.

11. Geometry, surface, finishing, inspection and monitoring

MEX geometry is bounded by nozzle access, road width/height, start/stop behaviour, cooling, green support, debinding transport, sintering stability and inspection. Thin walls need enough bonded roads to survive handling and thermal conversion. Small gaps can close through over-extrusion or shrinkage. Large sections can debind slowly. Enclosed channels can trap support, decomposition products or finishing media.

Lattices and gyroids expose the difference between printability and deliverability. Parenti et al.'s gyroid study provides a geometry-specific method for assessing extrusion printability [26]. Production qualification must extend that evidence through support removal, binder transport, sintering, strut/pore geometry and inspection. It must also include representative constrictions that challenge the qualified particle/agglomerate-to-orifice condition and detect composition drift or jamming. A clean exterior is not proof of an internally cleared and conforming lattice.

Surface condition inherits road contour, layer staircase, seams, support interface, adhered debris, open pores and sintering. Machining, tumbling, blasting, polishing or coating can alter dimensions, close or expose pores and introduce contamination. A roughness value is meaningful only with method, location, direction, filtering and material state. Surfaces inaccessible to finishing need as-sintered capability evidence.

Inspection combines complementary methods. Dimensional metrology measures accessible geometry. Mass/density methods average a volume. Metallography samples cut planes. Chemical analysis addresses selected elements. Mechanical tests address the specimen and orientation. Radiography or CT can detect some internal features subject to resolution, geometry, material and artefact limits. ISO/ASTM TR 52905 frames NDT selection and coverage boundaries [11]; it does not give universal acceptance criteria.

Green-state monitoring can include feed force or pressure, motor current, temperature, filament motion, extrusion mass, images and layer geometry. A pressure excursion can signal a blockage or viscosity change but cannot identify its cause alone. A normal camera image may miss an internal or sub-resolution interface defect. Every signal requires calibration, spatial/temporal registration, detection limits and a response rule.

Final evidence must remain linked to the deposited toolpath after shrinkage and possible machining. ISO/ASTM 52953 addresses registration of monitoring and quality-control data, while ISO/ASTM 52951 addresses data packages for AM parts [9,10]. A build coordinate may transform anisotropically; the data system needs the geometry/version and mapping used to associate an anomaly with the delivered region.

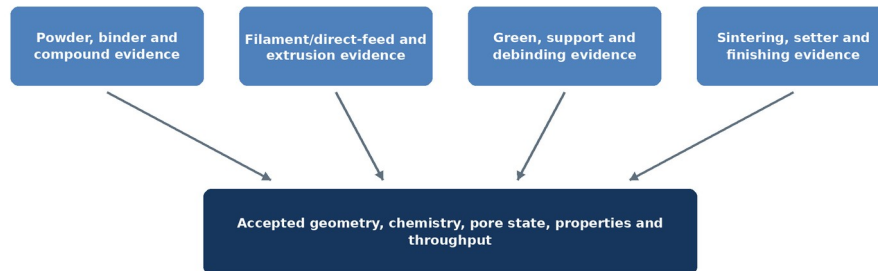


Figure 2. Part-linked evidence architecture for bound-metal material extrusion.

Disposition integrates rather than substitutes evidence. A missing-feed event can cause immediate hold or targeted inspection according to a validated rule. Passing density cannot waive a critical dimensional or chemistry failure. A normal coupon cannot clear a part whose section, orientation or furnace position is outside the correlation. Incomplete sensor or genealogy data is itself a controlled deviation.

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

Printer speed and printer price are incomplete denominators. The factory route includes compound preparation or purchase, incoming tests, pellet/filament manufacture and conditioning, spool or hopper loading, printing, cooling, support removal, green inspection, debinding queue, debinding, transfer where applicable, sintering, cooldown, setter removal, heat treatment/HIP where specified, finishing, cleaning, inspection, rework, scrap and release.

Effective cell throughput = accepted components ÷ complete elapsed factory-cell time.

Material efficiency = accepted-component mass ÷ released input mass across the same declared cell boundary.

Filament can simplify printer logistics and distributed handling when a stable qualified spool exists. Its manufacture and dimensional/mechanical rejection may occur upstream and remain hidden in a purchased-material price. Pellet/direct feed can remove spooling and exploit larger feed containers, but changeover, purge, screw/barrel cleaning, heat-up and residence control can dominate short runs. Economics must place these operations inside the same boundary.

Extrusion is pointwise and toolpath-dependent. More roads, contours, small features, starts/stops and support increase printer time. Larger nozzles or layers can raise deposition rate while changing surface, feature resolution, interfaces and debinding sections. A nominal volumetric flow is not accepted-part throughput.

Thermal capacity can be the bottleneck. Parts must share compatible binder-removal and sintering routes, setters, atmospheres, load arrangements and contamination constraints. Printer farms can overproduce green inventory for a furnace. Long furnace cycles, cooling and qualification lots shape work-in-process and lead time. Outsourced thermal treatment adds custody, transport, queue and evidence interfaces.

Safety is state-resolved. Bound feedstock can reduce direct handling of free powder during routine printer loading compared with a powder-bed process. It does not eliminate powder handling during compounding and feedstock manufacture, nor debris from damaged filament, granulation, purge, green machining, spills or waste. ISO/ASTM 52931 requires risk assessment across metallic-material subprocesses and waste [5].

Binder and additive hazards depend on the actual formulation. Heated extrusion can release degradation products; water or solvent debinding creates contaminated liquid and vapour streams; catalytic routes add reagent-specific controls; thermal debinding creates off-gas and condensate. “Water-removable,” “bio-based,” “low odour” or proprietary does not establish safe handling, exhaust adequacy or environmental superiority.

Furnaces add hot surfaces/parts, gas or vacuum hazards where applicable, ignition/asphyxiation potential, stored energy, off-gas, filters and maintenance exposure. Setters and furnace deposits can carry metals or binder products. Cooldown and safe service state are verified, not inferred from time. Operator responsibility and competence follow the actual tasks; ISO/ASTM 52926-1 provides general metal-AM operator architecture but no MEX-specific universal certificate [6].

NIOSH’s evaluation of one metal-powder AM facility demonstrates that exposure depends on actual task, location and control implementation [13]. It is not a bound-metal exposure limit or proof for another facility. Monitoring and legal compliance must be established locally for compounding, printing, debinding, furnace, finishing, waste and maintenance.

Environmental claims use declared system boundaries. Avoided subtractive waste or contained feed may be beneficial, while rejected filament/pellets, purge, support, solvents/water treatment, furnace energy, setters, machining stock, filters and scrap remain. Yield and furnace utilisation can reverse a printer-only comparison. Claims require measured mass/energy and disposition rather than labels such as “desktop,” “near-net” or “bio-based.”

13. Qualification architecture and selection gate

Qualification links site, personnel, materials, equipment, process, geometry, thermal conversion, inspection and change control. ISO/ASTM 52920 supplies the production-site framework [2]. ISO/ASTM 52901 clarifies purchased-part information and acceptance [7]. ISO/ASTM 52927 organises characteristics and corresponding test methods [8]. Data registration and packages follow ISO/ASTM 52953 and 52951 [9,10]. None alone qualifies bound-metal MEX.

Table 3. Bound-metal MEX factory qualification and selection gate

Gate	Minimum evidence	Fail or hold condition
Intended delivered state	Drawing/specification, alloy/chemistry, surface, pores, properties, cleanliness and service boundary	State or critical failure modes undefined
Powder/binder/compound release	Lot/batch genealogy, homogeneity, rheology, moisture, thermal history and relevant tests	Product or MIM grade used alone
Filament/direct-feed release	Filament geometry/mechanics/spool state or pellet/rod delivery, segregation and metering evidence	Feed identity or route-specific handling window unresolved
Equipment and build release	Feed path, hot end, nozzle, calibration, environment, toolpath/software and maintenance status	Relevant change or flow/nozzle drift uncontrolled
Green and support release	Spatial density/void evidence, inter-road/interlayer contact evidence distinct from intraroad packing, geometry, strength, support/interface removal and damage check	“100% infill,” bulk density or visual exterior used alone
Debinding/brown state	Validated removal mechanism, section/load family, mass/gas/chemistry evidence and brown integrity	Incomplete removal, residue, cracking or route equivalence unresolved
Sintering and setter	Furnace/load/atmosphere, setter, shrinkage, distortion, pores, chemistry and microstructure	Generic MIM cycle or unsupported scale factor substituted
Delivered part and inspection	Dimensions, surface, cleanliness, pores, chemistry, properties, coverage and uncertainty	Density or coupon used as sole acceptance
Factory, productivity and safety	Complete-cell capacity/yield, trained personnel, task controls, utilities and legal requirements	Furnace bottleneck, exposure or maintenance control incomplete
Change and transfer	Equivalence/requalification for powder, binder, feed form, machine, software, geometry, furnace and post-process	“Same alloy/settings/printer” used as equivalence

The route is selected when a suitable compound can be fed reproducibly, the geometry can be deposited and handled, binder can escape without damage, sintering can reach the required chemistry/pore/dimensional state, and the complete cell meets demand and safety requirements. It is held or rejected when filament/feed cannot remain stable, critical bead defects align with service loads, thick or closed features cannot debind, shrinkage cannot be predicted, setters cannot control distortion, chemistry is unstable, or inspection cannot cover a critical region.

Change control is broad because material and process are coupled. Powder supplier or surface, binder/additive batch or formulation, compounder, pellet/filament process, spool geometry, drive path, screw/piston, hot end, nozzle, firmware, slicer, toolpath, chamber, support/interface, debinding medium, furnace, atmosphere, setter, load arrangement, HIP/heat treatment or finishing can affect the delivered state. Nominally identical printers do not establish equivalence.

Equivalence is tiered. A change that can introduce a new failure mode, alter an unrepresented compound, feed, deposition, interface, debinding, sintering, setter or delivered-part state, or affect acceptance requires full requalification of the affected chain. A bounded change may use verification only when a documented causal assessment identifies the affected characteristics and a predeclared minimum evidence set confirms input genealogy, compound and feed-form state, calibrated deposition and interface formation, representative green geometry, actual debinding and furnace execution, setter/load position, delivered-state chemistry, pores, dimensions and properties, inspection capability and acceptance against existing limits. If that set is incomplete, its uncertainty overlaps a limit or the changed condition lies outside the validated domain, equivalence is not demonstrated and the route remains on hold.

Deviation handling preserves genealogy. Filament slip or break, pellet starvation, pressure/temperature excursion, nozzle blockage, layer anomaly, support damage, green crack, mass-loss anomaly, furnace excursion, broken setter, unexpected shrinkage, failed chemistry or missing data creates a hold and documented disposition. Rework is permitted only if its material-state effect is qualified.

The qualification file lets an independent reviewer reconstruct why the particular component was accepted. It includes requirements, risk analysis, input releases, compound/feedstock versions, equipment/calibration, build and thermal definitions, operator responsibility, job/load location, monitoring, state-specific inspection, uncertainty, deviations and release authority. A technology label or successful demonstration is not a production qualification.

14. Conclusions and research priorities

Bound-metal material extrusion is not low-temperature metal printing. It is polymer-composite shaping followed by binder removal and metallurgical densification. Filament feed translates compound design into a mechanically demanding spool state;

pellet, rod, piston and screw feed exchange that burden for metering, residence and cleaning controls. Both create a spatial green road architecture whose interfaces can survive into the final metal.

A defensible industrial programme follows five rules:

1. qualify powder, binder, compound and feed form as a coupled system rather than by alloy or product name;
2. measure deposited road/interface architecture instead of treating nominal slicer infill as density;
3. keep green, brown, sintered, HIPed, heat-treated, machined and delivered states separate;
4. qualify debinding, shrinkage, supports/setters and final properties on representative geometry and loads; and
5. compare filament and direct-feed routes using accepted complete-cell throughput, safety and part-linked evidence.

Priority research should improve compound-homogeneity and segregation metrology; filament mechanics linked to feed reliability; direct-feed residence and dosing models; nozzle-wear and mass-flow monitoring; three-dimensional green void mapping; interfacial particle-contact and sintering-neck-density metrology distinct from intraroad packing; quantitative interface-to-final-defect correlation; geometry-aware solvent/gas transport during debinding; in-situ brown-state and shrinkage measurement; setter/friction models; compensation validated outside its training set; and transfer protocols across compounders, printers and furnaces.

Until those links close for a specified route, claims such as “desktop metal,” “powder-free,” “safe,” “100% infill,” “MIM-equivalent,” “fully dense,” “any alloy,” “low cost” and one shrinkage factor remain incomplete. The capability belongs to a qualified powder–binder–feedstock–extruder–thermal–post-process–factory system.

References

- [1] ISO/ASTM 52900:2021. *Additive manufacturing — General principles — Fundamentals and vocabulary*. Edition 2; confirmed in 2025. <https://www.iso.org/standard/74514.html>
- [2] ISO/ASTM 52920:2023. *Additive manufacturing — Qualification principles — Requirements for industrial additive manufacturing processes and production sites*. Edition 1. <https://www.iso.org/standard/76911.html>
- [3] ISO/ASTM 52903-1:2020. *Additive manufacturing — Material extrusion-based additive manufacturing of plastic materials — Part 1: Feedstock materials*. Edition 1. <https://www.iso.org/standard/67290.html>
- [4] ISO/ASTM 52903-2:2020. *Additive manufacturing — Material extrusion-based additive manufacturing of plastic materials — Part 2: Process equipment*. Edition 1; confirmed in 2022. <https://www.iso.org/standard/69968.html>
- [5] ISO/ASTM 52931:2023. *Additive manufacturing of metals — Environment, health and safety — General principles for use of metallic materials*. Edition 1. <https://www.iso.org/standard/74641.html>
- [6] ISO/ASTM 52926-1:2023. *Additive manufacturing of metals — Qualification principles — Part 1: General qualification of operators*. Edition 1. <https://www.iso.org/standard/76827.html>
- [7] ISO/ASTM 52901:2017. *Additive manufacturing — General principles — Requirements for purchased AM parts*. Edition 1; confirmed in 2023. <https://www.iso.org/standard/67288.html>
- [8] ISO/ASTM 52927:2024. *Additive manufacturing — General principles — Main characteristics and corresponding test methods*. Edition 1. <https://www.iso.org/standard/81802.html>
- [9] ISO/ASTM 52953:2025. *Additive manufacturing for metals — General principles — Registration of data acquired from process monitoring and for quality control*. Edition 1. <https://www.iso.org/standard/84117.html>
- [10] ISO/ASTM 52951:2026. *Additive manufacturing — Data — Data packages for AM parts*. Edition 1. <https://www.iso.org/standard/76828.html>
- [11] ISO/ASTM TR 52905:2023. *Additive manufacturing of metals — Non-destructive testing and evaluation — Defect detection in parts*. Edition 1. <https://www.iso.org/standard/82539.html>
- [12] ISO/ASTM 52907:2019. *Additive manufacturing — Feedstock materials — Methods to characterize metal powders*. Edition 1; confirmed in 2025. <https://www.iso.org/standard/73565.html>
- [13] Stefaniak, A.B., Brusak, E.D., Bowers, L.N., Friend, S., Barnes, C. and Qi, C. *Evaluation of Metals Exposure in a Metal Powder Additive Manufacturing Facility*. NIOSH Health Hazard Evaluation Report 2023-0034-3409 (2025). <https://www.cdc.gov/niosh/hhe/reports/pdfs/2023-0034-3409.pdf>
- [14] Thompson, Y., Gonzalez-Gutierrez, J., Kukla, C. and Felfer, P. *Fused filament fabrication, debinding and sintering as a low cost additive manufacturing method of 316L stainless steel*. *Additive Manufacturing* 30 (2019) 100861. <https://doi.org/10.1016/j.addma.2019.100861>
- [15] Gong, H., Snelling, D., Kardel, K. and Carrano, A. *Comparison of stainless steel 316L parts made by FDM- and SLM-based additive manufacturing processes*. *JOM* 71 (2019) 880–885. <https://doi.org/10.1007/s11837-018-3207-3>
- [16] Godec, D., Cano, S., Holzer, C. and Gonzalez-Gutierrez, J. *Optimization of the 3D Printing Parameters for Tensile Properties of Specimens Produced by Fused Filament Fabrication of 17-4PH Stainless Steel*. *Materials* 13 (2020) 774. <https://doi.org/10.3390/ma13030774>
- [17] Tosto, C., Tirillò, J., Sarasini, F. and Cicala, G. *Hybrid Metal/Polymer Filaments for Fused Filament Fabrication (FFF) to Print Metal Parts*. *Applied Sciences* 11 (2021) 1444. <https://doi.org/10.3390/app11041444>
- [18] Singh, G., Missiaen, J.-M., Bouvard, D. and Chaix, J.-M. *Additive manufacturing of 17-4 PH steel using metal injection molding feedstock: Analysis of 3D extrusion printing, debinding and sintering*. *Additive Manufacturing* 47 (2021) 102287. <https://doi.org/10.1016/j.addma.2021.102287>
- [19] Sadaf, M., Bragaglia, M. and Nanni, F. *A simple route for additive manufacturing of 316L stainless steel via Fused Filament Fabrication*. *Journal of Manufacturing Processes* 67 (2021) 141–150. <https://doi.org/10.1016/j.jmapro.2021.04.055>
- [20] Waalkes, L., Längerich, J., Holbe, F. and Emmelmann, C. *Feasibility study on piston-based feedstock fabrication with Ti-6Al-4V metal injection molding feedstock*. *Additive Manufacturing* 35 (2020) 101207. <https://doi.org/10.1016/j.addma.2020.101207>
- [21] Eickhoff, R., Antusch, S., Baumgärtner, S., Nötzel, D. and Hanemann, T. *Feedstock Development for Material Extrusion-Based Printing of Ti6Al4V Parts*. *Materials* 15 (2022) 6442. <https://doi.org/10.3390/ma15186442>
- [22] Eickhoff, R., Antusch, S., Nötzel, D. and Hanemann, T. *New Partially Water-Soluble Feedstocks for Additive Manufacturing of Ti6Al4V Parts by Material Extrusion*. *Materials* 16 (2023) 3162. <https://doi.org/10.3390/ma16083162>
- [23] Zhang, Y., Bai, S., Riede, M., Garratt, E. and Roch, A. *A comprehensive study on fused filament fabrication of Ti-6Al-4V structures*. *Additive Manufacturing* 34 (2020) 101256. <https://doi.org/10.1016/j.addma.2020.101256>
- [24] Singh, P., Balla, V.K., Atre, S.V., German, R.M. and Kate, K.H. *Factors affecting properties of Ti-6Al-4V alloy additive manufactured by metal fused filament fabrication*. *Powder Technology* 386 (2021) 9–19. <https://doi.org/10.1016/j.powtec.2021.03.026>
- [25] Gabilondo, M., Cearsolo, X., Arrue, M. and Castro, F. *Influence of Build Orientation, Chamber Temperature and Infill Pattern on Mechanical Properties of 316L Parts Manufactured by Bound Metal Deposition*. *Materials* 15 (2022) 1183. <https://doi.org/10.3390/ma15031183>
- [26] Parenti, P., Puccio, D., Colosimo, B.M. and Semeraro, Q. *A new solution for assessing the printability of 17-4 PH gyroids produced via extrusion-based metal AM*. *Journal of Manufacturing Processes* 74 (2022) 557–572. <https://doi.org/10.1016/j.jmapro.2021.12.043>
- [27] Mancía, T., Forcelllese, P., Bellezze, T. and Simoncini, M. *Effect of build-up orientation angle and printing speed on mechanical properties and micro- and macro-defect formation in 17-4 PH stainless steel components manufactured by Bound Metal Deposition*. *International Journal of Advanced Manufacturing Technology* 132 (2024) 4285–4295. <https://doi.org/10.1007/s00170-024-13628-2>
- [28] Jiang, S., Xu, Z., Li, S. et al. *Study on the Forming and Mechanical Properties of 17-4PH Parts Fabricated by Metal Material Extrusion Additive Manufacturing Technique*. *Journal of Materials Engineering and Performance* 34 (2025) 15928–15943. <https://doi.org/10.1007/s11665-024-10355-3>
- [29] Shima, H., Yamanaka, K., Mori, M., Yuan, C., Nitta, K. and Chiba, A. *Material extrusion additive manufacturing of 17-4PH stainless steel via bound metal deposition: Densification, microstructures, and tensile properties*. *Engineering Science in Additive Manufacturing* 2 (2026) 026120006. <https://doi.org/10.36922/ESAM026120006>

- [30] Karimi, N., Zurob, H., Fayazfar, R.H., Sahai, A. and Sharma, R.S. *Nickel material extrusion additive manufacturing with spiky carbonyl powder: Feedstock development, debinding, and sintering*. Journal of Materials Research 41 (2026) 997–1009. <https://doi.org/10.1557/s43578-026-01808-7>
- [31] Lengauer, W., Duretek, I., Fürst, M., Schwarz, V., Gonzalez-Gutierrez, J., Schuschnigg, S., Kukla, C., Kitzmantel, M., Neubauer, E., Lieberwirth, C. and Morrison, V. *Fabrication and properties of extrusion-based 3D-printed hardmetal and cermet components*. International Journal of Refractory Metals and Hard Materials 82 (2019) 141–149. <https://doi.org/10.1016/j.ijrmhm.2019.04.011>
- [32] Bose, A., Reidy, J.P., Tuncer, N. and Jorgensen, L. *Processing of tungsten heavy alloy by extrusion-based additive manufacturing*. International Journal of Refractory Metals and Hard Materials 110 (2023) 106021. <https://doi.org/10.1016/j.ijrmhm.2022.106021>
- [33] 3Dresyns. *Nano & micron raw materials for manufacturing 2D & 3D exotic materials*. Accessed 1 September 2026. <https://www.3dresyns.com/pages/nano-micron-raw-materials-for-manufacturing-2d-3d-exotic-materials>
- [34] Gloeckle, C., Konkol, T., Jacobs, O., Limberg, W., Ebel, T. and Handge, U.A. *Processing of Highly Filled Polymer-Metal Feedstocks for Fused Filament Fabrication and the Production of Metallic Implants*. Materials 13 (2020) 4413. <https://doi.org/10.3390/ma13194413>
- [35] Segurola, J. *Industrial Additive Manufacturing Technology Selection: Process Families, Material States, Qualification Burden and Decision Gates*. ER-139, Version 0.3 (2026). Controlled corpus record; no DOI assigned.
- [36] Segurola, J. *Direct and Indirect Additive Manufacturing for Advanced Ceramics and Metals: Evidence-Based Route Selection*. ER-049, Version 1.1 (2026). <https://doi.org/10.5281/zenodo.22048071>
- [37] Segurola, J. *Polymer Material Extrusion for Industrial Production: Filament FFF/FDM, Pellet Extrusion, Reactive Screw/Large-Format Extrusion, Anisotropy, Throughput and Qualification*. ER-140, Version 0.2 (2026). Controlled corpus record; DOI not yet registered.
- [38] Segurola, J. *Direct Ink Writing and Paste Extrusion: Silicones, Hydrogels, Highly Filled Polymers, Shape Retention, Drying/Cure and Qualification*. ER-144, Version 0.2 (2026). Controlled corpus record; DOI not yet registered.