

# Polymer Powder-Bed Additive Manufacturing: SLS, MJF, HSS and SAF

*Powder Reuse, Thermal History, Surface State and Production Qualification*

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## Statement of Significance

Polymer powder-bed additive manufacturing is often selected because surrounding powder can carry complex shapes without discrete supports. That advantage is real but incomplete. Powder must first be released, conditioned, blended and spread; selective energy or absorbing agents must then operate inside a controlled thermal window; every location accumulates a different time-temperature history; and cooling, unpacking, depowdering, finishing and inspection remain part of the production cell. Used powder can change even when it has not been fused, while a channel that builds successfully can still fail because trapped powder cannot be removed or verified. ER-141 compares laser PBF/SLS, Multi Jet Fusion, High Speed Sintering and Selective Absorption Fusion as different energy-and-material architectures. It places powder history, bed position, geometry, surface state, recovery and accepted yield inside one qualification boundary and rejects universal refresh fractions, machine-speed rankings and bulk-powder-to-part equivalence.

**Keywords:** *polymer powder bed fusion; selective laser sintering; SLS; laser PBF; PBF-LB/P; Multi Jet Fusion; MJF; High Speed Sintering; HSS; Selective Absorption Fusion; SAF; polyamide 12; powder reuse; thermal history; depowdering; process qualification*

## Abstract

Polymer powder-bed fusion contains several architectures that share sequential powder spreading but create selective consolidation differently. Laser PBF, commonly called selective laser sintering, scans a focused energy source. Multi Jet Fusion, High Speed Sintering and Selective Absorption Fusion pattern radiation-absorbing or boundary-modifying fluids and use bed-wide infrared exposure within system-specific thermal strategies. This qualitative engineering review follows all four routes from released powder to accepted component. It examines particle size and shape, flow and packing, moisture and storage, spreading, preheat, optical and agent coupling, coalescence, crystallisation, repeated hot exposure, cooling, distortion, powder segregation and refresh, nesting, internal depowdering, surface state, porosity, anisotropy, post-processing, safety, complete-cell throughput and qualification. Primary studies demonstrate that powder ageing depends on bounded material and exposure histories; coalescence is non-isothermal and rheology-dependent; build position and geometry can alter thermal, dimensional, surface and mechanical states; and surrounding powder does not guarantee recoverable internal passages. No universal reuse percentage, energy-density formula, isotropy claim or dimensional rule survives transfer across polymers, machines and architectures. The resulting selection gate requires traceable powder genealogy, build-layout control, measured thermal and delivery states, qualified recovery and inspection, and accepted-component yield. Metal PBF, construction-scale systems, bound powders and ceramic sintering are outside scope.

## 1. Purpose and scope

ER-141 applies the state-resolved framework of ER-139 to polymer powder-bed additive manufacturing. ISO/ASTM 52900:2021 provides common additive-manufacturing vocabulary [1]. In this review, laser PBF of polymers is described as PBF-LB/P where the standard designation is useful and as SLS when discussing the common industrial name or literature that uses it. The terminology does not turn every laser, material or process window into an equivalent route.

ISO/ASTM 52911-2:2019 addresses design for laser-based PBF of polymers [3]. ISO/ASTM 52925:2022 addresses polymer-feedstock qualification for PBF-LB/P, principally for PA12 and PA11 [4]. ISO/ASTM 52936-1:2023, 52924:2023 and 52927:2024 provide qualification, property-classification and test-method structures [5-7]. ASTM F3091/F3091M-14(2021) supplies a specification for PBF plastic materials [8]. ISO/ASTM 52920:2023 places the machine and material inside an industrial process and production-site qualification system [2]. None of these documents establishes that a nominal powder or a parameter file is qualified for a particular component.

The review covers laser PBF/SLS, MJF, HSS and SAF when the delivered object is a polymer or polymer-composite component. It includes powder conditioning and reuse, build packing, cooling, depowdering and finishing because those stages determine capacity and acceptance. Metal PBF belongs to ER-145 and ER-146. Polymer-binder PBF of metals, ceramics and unusual powders belongs to ER-155; ceramic and sand binder jetting belongs to ER-153; and bound-ceramic material extrusion belongs to ER-154. Those routes are outside ER-141 because debinding and sintering create their delivered material state. Macroscopic construction materials are excluded. Performance claims for named commercial systems are outside scope unless independently supported for a declared material, machine, build and endpoint.

## 2. Four architectures inside polymer powder-bed fusion

All four routes create a layer of powder and selectively consolidate a cross-section before repeating the sequence. Their selective mechanism, thermal field and control variables differ.

Laser PBF scans a focused beam across selected regions. Absorption, beam state, spot and scan strategy determine local input, while bed temperature and prior passes shape the thermal boundary condition. Scan vectors create temporal and spatial differences inside one layer. A nominal power and speed pair does not establish a local material history because spot condition, absorptivity, layer state, path ordering and heat loss also matter.

MJF patterns fusing and detailing agents with inkjet arrays and exposes the layer to infrared energy. The fusing agent changes absorption in intended regions; detailing chemistry and thermal strategy influence edges. Nozzle delivery, agent condition, powder-agent compatibility and the radiation field therefore join spreading and temperature as controlled states. An agent command is not proof of delivered drop mass or optical effect.

HSS selectively deposits a radiation-absorbing ink and uses infrared irradiation to fuse the patterned regions. Ellis et al. framed material requirements for HSS [17], while Bharaj et al. and Kemnitzer et al. demonstrated bounded PMMA and PA12 implementations [18,19]. Those studies establish feasibility and causal variables, not equivalence among HSS platforms or materials.

SAF uses selectively jetted high-absorption fluid, infrared energy and a powder-management architecture described by its manufacturer [27]. That source can establish what the commercial architecture contains. It cannot independently establish speed, cost, yield, isotropy or superiority. SAF therefore enters this review as a distinct route requiring its own qualified material, fluid, spread, thermal and recovery evidence.

Table 1. Polymer powder-bed architectures require different control records

| Axis                         | Laser PBF/SLS                                                        | MJF                                                             | HSS                                                      | SAF                                                                           |
|------------------------------|----------------------------------------------------------------------|-----------------------------------------------------------------|----------------------------------------------------------|-------------------------------------------------------------------------------|
| Selective mechanism          | Scanned laser energy                                                 | Jetted fusing/detailing agents plus infrared                    | Jetted absorbing ink plus infrared                       | Jetted high-absorption fluid plus infrared                                    |
| Bed-wide state               | Preheat, layer exposure and scan-dependent heat                      | Powder, agents, lamps and thermal-control sequence              | Powder, ink, radiation field and layer timing            | Powder spreading/recirculation, fluid, radiation and thermal-control sequence |
| Main conditional opportunity | Direct vector control and established polymer-laser and PBF evidence | Area-wise patterning with system-defined edge control           | Area-wise absorbing pattern over a powder layer          | Area-wise fluid/IR route integrated with system powder handling               |
| Characteristic limitation    | Scan-time and vector thermal gradients, optical-state sensitivity    | Printhead/nozzle and agent state, edge chemistry, contamination | Ink compatibility, coverage and non-uniform irradiation  | System-specific fluid, spread, cooling and recovery dependencies              |
| Change-control focus         | Laser/optics, scan, layer, bed temperature and powder                | Agent lots, printheads, lamps, powder, layout and thermal state | Ink, printheads, lamps, powder, layout and thermal state | Fluid, roller/spread system, lamps, powder circulation and cooling            |

Architecture labels do not rank production performance. A laser route may be constrained by scan time or cooling; an agent route may pattern quickly but remain constrained by bed preparation, thermal dwell, cooling, unpacking, powder recovery or finishing. The correct comparison is accepted components per complete cell cycle.

## 3. State-resolved process chain

The process starts with powder release and ends after the final conditioned component has passed acceptance. A lot is received, identified, stored and sampled. Virgin, used or blended powder is conditioned and loaded. Each layer is metered and spread, heated, selectively exposed, and carried through subsequent layer cycles. The completed build cools, often for a substantial fraction of total elapsed time, before the cake is unpacked. Parts are excavated, depowdered, cleaned, finished, conditioned, measured and released. Recoverable powder is sieved, segregated, tested, blended or rejected under a declared rule.

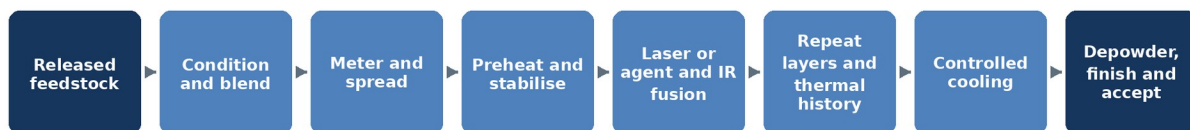


Figure 1. State-resolved polymer powder-bed production chain

Each record must identify the represented state. A virgin-powder certificate does not describe a blend containing powder exposed to several hot builds. A bed-temperature setpoint does not describe local particle temperature. A density from one coupon does not establish the porosity of an internal feature elsewhere in a packed build. A dimension measured immediately after unpacking may not equal the conditioned dimension. Industrial qualification depends on preserving these distinctions rather than compressing them into a machine recipe.

## 4. Powder identity, morphology, flow and release

Polymer identity is necessary but insufficient. Powder release should control formulation, polymer grade, additives, pigment, reinforcement, supplier and lot. It should also address particle-size distribution, particle shape, fines and agglomerates, apparent and tapped density where relevant, flow or spread response, moisture and storage history, thermal transitions, melt behaviour and any validated chemical or molecular indicator. Bain et al. provide benchmark physical-property measurements for PBF PA12 and illustrate the value of traceable measurement methods and interlaboratory comparability [10]. The benchmark does not turn PA12 into one invariant feedstock.

Particle geometry influences flow, packing, optical interaction and local pore formation. A free-flowing bulk test can miss layer-specific behaviour because the recoater imposes a thin-layer shear and compaction history. Fines may fill voids or increase cohesion and dust; coarse or irregular particles may disrupt a layer or change packing. The release plan must link the chosen powder tests to unacceptable bed states rather than collect generic certificate values.

Thermal and rheological windows are coupled. Schmid, Amado and Wegener explained that polymer suitability for SLS depends on powder behaviour and a useful processing window involving melting, crystallisation and melt response [9]. The often-used idea of a wide sintering window is a screening concept, not component qualification. Heating rate, dwell, molecular state, additives, atmosphere, powder geometry and the actual machine thermal field can shift behaviour.

Moisture and contamination require route-specific controls. Moisture can alter flow, agglomeration, hydrolysis-sensitive polymers, surface state or agent delivery. Cross-contamination can arise from recovery tools, sieves, hoses, blasting systems, shared containers or a prior material. Colour or fluorescence is not an adequate contamination test when small fractions can alter absorption, chemistry or regulated composition. A factory should define dedicated or verified-clean contact equipment, closed containers, exposure-time limits, sampling locations and disposition rules.

ISO/ASTM 52925 is especially relevant to PA11 and PA12 [4]. Its concepts should not be silently promoted into universal limits for thermoplastic elastomers, high-temperature polymers or filled powders. A new formulation needs evidence for its own powder, thermal, fusion, recovery and ageing states.

## 5. Spreading and powder-bed formation

Layer formation converts a bulk powder into the actual feed geometry of PBF. Metering must provide enough material; the roller or blade must transport and distribute it; and the layer must remain sufficiently uniform for the selective mechanism. Recoater geometry, speed, rotation, gap, wear, powder head, temperature, electrostatics and previously fused protrusions can change the layer.

An acceptable average mass does not exclude local streaks, waves, voids, drag marks or agglomerates. Thin walls or edge regions can be affected by a defect that contributes little to bed-average statistics. Klippstein et al. demonstrated powder-spread monitoring and linked spread conditions with part-property evidence in a defined polymer laser-sintering study [15]. The transferable conclusion is that spreading can be measured and causally related to quality. Their data do not establish one image threshold for every powder or component.

The factory record should distinguish commanded layer thickness from verified layer formation. Useful evidence can include recoater position and load, images, surface-height data, powder delivery mass, temperature and event detection. A signal becomes a control only after the organisation defines the unacceptable state it detects, coverage of critical zones, action limits, false-positive and false-negative handling, and disposition of affected layers or builds.

Spread qualification must include transients. The first layer, feed-bin transitions, interruptions, recoater changes, powder additions and build regions near boundaries can differ from steady central layers. A reused-powder blend can spread differently after handling even when its bulk particle-size distribution appears unchanged. A parameter file cannot compensate for an uncontrolled powder head or damaged spreading element.

## 6. Selective fusion and energy or agent coupling

Fusion requires particles to absorb energy, heat, deform and coalesce without unacceptable degradation, distortion or loss of detail. Hejmady et al. visualised laser sintering of polystyrene particle pairs and found a non-isothermal interaction among temperature-dependent rheology, particle scale and laser conditions [16]. The study isolates a mechanism. It does not define the consolidation of a packed semi-crystalline PA12 layer, a filled powder or an agent-patterned build.

In laser PBF, delivered optical state includes laser output, beam profile, focus, spot position, scan speed, hatch spacing, contour strategy, delay, overlap and optical cleanliness. A single volumetric or areal energy-density expression can combine command variables but cannot uniquely represent absorptivity, transient temperature, heat loss, melt viscosity or scan ordering. Equal calculated density can arise from unequal physical histories. It is therefore a recipe descriptor, not a transferable qualification metric.

In agent-based routes, printhead and fluid states join irradiation. Drop formation, missing or deflected nozzles, fluid age, temperature, viscosity, surface interaction, penetration and local coverage can change optical absorption and edge behaviour. Lamp output, spectrum, distance, motion and contamination influence the resulting heat. Calibration should connect delivery and radiation measurements to a material response, and any compensation algorithm must remain under software and change control.

MJF, HSS and SAF must not be collapsed into a common fluid percentage or lamp setting. O'Connor and Dowling studied MJF PA12 and glass-bead-filled PA12 within one process [20]. Ellis et al., Bharaj et al. and Kemnitzer et al. provide HSS evidence for

defined materials and systems [17-19]. The SAF design guide establishes a commercial fluid-and-infrared architecture [27]. Together they justify common questions about selective absorption, but not common values or performance rankings.

## 7. Thermal history, crystallisation, cooling and distortion

The powder bed is a thermal store. Every voxel experiences initial preheat, selective exposure or surrounding-bed heat, subsequent layer cycles, dwell while the rest of the build completes, and cooling after the last layer. Position in height and plan, neighbouring fused volume, packing density, scan or agent sequence and boundary proximity can change that history.

Semi-crystalline polymers add melting and crystallisation kinetics to coalescence. Neugebauer et al. quantified isothermal and non-isothermal crystallisation kinetics for PA12 used in laser sintering [13]. Kiani et al. related measured thermal history to mechanical properties in a bounded PA12 process [14]. These studies support material- and location-specific thermal records. They do not establish a universal powder-bed temperature or crystallisation schedule.

Too little local fusion can leave weak necks, lack of consolidation or high porosity. Excessive heat can reduce definition, fuse surrounding powder, promote distortion or degrade material. Thermal gradients and constrained shrinkage can create curl. Klamert et al. used simultaneous profilometry and thermal imaging to study curling in a defined polyamide PBF process [23]. The result supports combined geometry-and-temperature monitoring, not a universal curl limit.

Cooling is a production operation, not dead time. Premature excavation can change warpage, residual stress, crystallinity or surface damage. A conservative cool-down may protect quality while limiting cell capacity and increasing work-in-process. The qualified route should define the cooling boundary, measurement locations or justified surrogate, cake handling, transfer environment and condition at unpacking. If accelerated or external cooling is introduced, it is a process change requiring dimensional and property evidence.

Build layout is therefore part of the recipe. A tightly packed build can improve nominal machine utilisation while changing heat accumulation, gas or radiation paths, powder access, cooling time and the number of parts put at risk by one build-level deviation. Coupons placed in convenient locations cannot automatically represent thermally extreme or geometry-critical components.

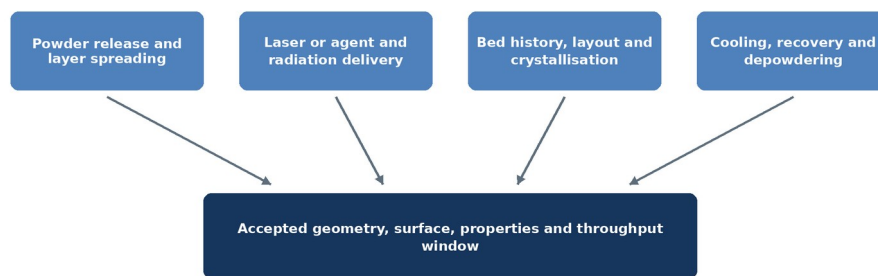


Figure 2. Coupled powder, fusion, thermal and recovery window

Table 2. Mechanism-to-defect and evidence matrix

| Process stage                | Controlling variables                                                   | Representative unacceptable state                                | Minimum discriminating evidence                                                    |
|------------------------------|-------------------------------------------------------------------------|------------------------------------------------------------------|------------------------------------------------------------------------------------|
| <b>Powder release</b>        | Lot, composition, particles, moisture, storage, thermal/melt state      | Unspreadable, contaminated or aged feed passes on polymer name   | Traceable sample plan, powder and thermal tests tied to release limits             |
| <b>Blending/reuse</b>        | Exposure genealogy, fractions, mixing, segregation, sieve and container | Nominal refresh ratio hides unequal hot history or contamination | Mass balance, blend identity, exposure classes and verified homogeneity            |
| <b>Spreading</b>             | Delivery mass, recoater state, speed, gap, powder head and temperature  | Streak, void, wave, drag or local thin layer                     | Layer-resolved monitoring or validated spread checks with coverage record          |
| <b>Selective input</b>       | Laser/optics/scan or fluid/printhead/lamp state                         | Underfusion, bleed, missing region or loss of edge definition    | Calibrated delivery evidence plus process response in representative zones         |
| <b>Thermal cycle</b>         | Bed field, layout, height, dwell, neighbours and cooling                | Curl, degradation, uncontrolled crystallinity or fused cake      | Spatial/temporal thermal evidence and conditioned dimensional/property checks      |
| <b>Unpacking/depowdering</b> | Cake state, access, tools, pressure, media and time                     | Damage, trapped powder or inaccessible internal surface          | Recovery instruction, mass/visual/CT or function evidence appropriate to feature   |
| <b>Final acceptance</b>      | Orientation, porosity, surface, conditioning, intended load             | Generic coupon passes while critical component feature fails     | Part-linked dimensions, surface, internal and functional evidence with uncertainty |

## 8. Reuse, refresh, contamination and traceability

Unfused powder is not necessarily unchanged powder. Material adjacent to the fused region and material elsewhere in the cake can experience different temperature and time. Recovery then adds handling, air exposure, sieving, mixing and storage. A label such as used once discards both the magnitude and spatial distribution of that history.

Pham, Dotchev and Yusoff found time and temperature to be influential in deterioration of the PA12 powder they studied [11]. Dotchev and Yusoff evaluated recycling of PA12-based powder and used melt-flow behaviour within a defined PA2200 system [12]. The correct transferable practice is to establish material- and route-specific indicators and limits. Their reported conditions do not create a universal cycle count, refresh ratio or melt-flow threshold.

A robust powder genealogy separates at least virgin lot, recovered source build, exposure class, sieve or conditioning operation, blend event, storage interval and destination build. Mass balance should account for loaded powder, fused parts, retained samples, spillage, waste, unrecovered cake and powder returned to inventory. This does not require tracking every particle. It requires enough resolution to prevent an uncontrolled average from masking an out-of-limit fraction.

Refresh ratio is an input to validation, not a release result. A fixed percentage can fail when build height, dwell, packing, polymer, machine thermal field or powder age changes. Conversely, automatic rejection after one exposure can waste material without improving acceptance. The validated rule should link defined exposure and blending states to powder tests, spread behaviour, representative part evidence and a final acceptance endpoint.

Segregation can occur during conveying, sieving and blending, particularly with fillers, pigments, broad particle distributions or agglomerates. A nominal composition after gravimetric mixing does not prove uniform delivery. Sampling should address container geometry and mixing method. Introduction of a new sieve, recovery station, transfer hose, antistatic practice or cleaning chemistry can change contamination and particle state and belongs under change control.

## 9. Geometry, nesting, surface and depowdering

The powder bed supports many overhangs and disconnected geometries during building, reducing the need for attached support structures. This does not make geometry unconstrained. Feature scale competes with particle size, layer thickness, optical or fluid spread, heat conduction, edge-control strategy, shrinkage and finishing allowance. Down-facing and upward-facing surfaces experience different boundary conditions, while stair stepping remains orientation-dependent.

Surface state is created by partially fused particles, layer contour, thermal bleed, powder removal and finishing. Roughness can vary with orientation, position and process architecture. Sağbaş et al. observed location-dependent dimensional and surface differences across a defined MJF PA12 build and associated them with non-uniform heating/cooling evidence [22]. Peterson et al. reported geometry-related mechanical, thermal and microstructural differences in a defined MJF PA12 study [25]. These results require build-layout control and representative sampling; they do not supply universal tolerances.

Nesting affects both capacity and physics. More components per build can reduce nominal machine time per item, yet dense or uneven placement can alter heat, cooling and powder access. Orientation may improve one surface or packing metric while worsening another feature, property direction or depowdering route. A nesting algorithm is therefore part of the qualified build definition, including software revision, clearance rules, protected zones and any permitted automatic rearrangement.

Internal channels are a decisive no-go boundary. Surrounding powder can carry the channel during fusion, but loose or lightly sintered powder must later travel through an opening under gravity, air, vibration, vacuum or another controlled method. Curvature, constrictions, branches, length, surface attraction and unintended cake fusion can trap material. Raz, Chval and Faitova examined accuracy and powder-removal limits in bounded MJF geometries [24]. Their dimensions are not universal design rules. The factory must validate its own material, geometry, build orientation, thermal state and removal method.

Depowdering evidence should match risk. Direct visual access may be adequate for an open feature. A safety- or function-critical hidden passage may require mass balance, borescope, computed tomography, flow, pressure-drop or cleanliness evidence. If residual powder cannot be removed or verified without damaging the part, the geometry is not industrially qualified even when the build completes.

Finishing can include blasting, tumbling, dyeing, sealing, chemical smoothing, coating, machining or thermal treatment. These operations can alter dimensions, surface, porosity, colour, chemistry and mechanical state. They also create capacity, worker-exposure and waste burdens. The drawing and route record must distinguish as-built, depowdered, finished and conditioned surfaces.

## 10. Porosity, anisotropy and property evidence

Consolidation develops through particle heating, deformation, coalescence and cooling. Incomplete fusion can retain particle boundaries and interconnected or isolated pores. Excessive heat can reduce definition or alter material. Porosity volume alone may not describe pore size, shape, orientation, connectivity or location, all of which can affect mechanical, fluid and surface performance.

Abbott, Sperry and Crane compared porosity and mechanical properties for PA12 made by laser PBF and MJF [21]. O'Connor and Dowling compared unfilled and glass-bead-filled PA12 in a defined MJF route [20]. Their results show that architecture, formulation and porosity/property relationships require direct evidence. They do not establish one density threshold, one glass-bead benefit or equivalence to moulded PA12.

Polymer-PBF components are sometimes marketed as isotropic because the bed is thermally supported and discrete extrusion roads are absent. That description is too strong for qualification. Layering, scan or agent sequence, vertical thermal history, build position, geometry, cooling and crystallisation can create directional or location-dependent behaviour. The required test matrix should be driven by load, environment and failure mode rather than a generic statement that the process is more isotropic than another route.

Test specimens must be traceable to powder state, build, location, orientation, geometry, cooling and post-processing. ISO/ASTM 52936-1 provides general principles for preparation of PBF-LB polymer test specimens [5], while ISO/ASTM 52924 classifies polymer-part properties [6]. These structures help define evidence. A separately built coupon cannot represent a packed production build unless equivalence has been demonstrated.

Conditioning matters for polyamides and other moisture-sensitive polymers. Dimensions and properties can change between dry-as-built, laboratory-conditioned and service-equilibrated states. Acceptance should declare temperature, humidity, time and any drying or ageing treatment. The corpus treatment of environmental ageing, state definition and property retention is developed in ER-072 [28]; ER-141 applies that state-resolved requirement to polymer-PBF components rather than re-establishing a general ageing method. Supplier data for virgin powder or moulded plaques cannot replace printed, post-processed and conditioned component evidence.

## 11. Throughput, automation and factory economics

Polymer PBF can place many parts within one three-dimensional build, but machine occupancy and accepted output depend on more than selective exposure. The relevant denominator is:

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

Elapsed time includes powder sampling and blending, loading, warm-up, layer spreading, selective processing, pauses, cooling, cake transfer, unpacking, sieving and recovery, depowdering, finishing, conditioning, inspection, queue time and rework. Yield must include build-level loss, damaged parts, trapped-powder rejection, dimensional nonconformance, cosmetic downgrades and destructive-test sampling.

Area-wise agent deposition can reduce the dependence of selective-processing time on vector length, while laser scanning can offer direct vector control. Neither observation determines accepted throughput. A fast layer can be offset by thermal dwell, cooling, printhead maintenance, agent handling, recovery or finishing. A densely nested build can lower nominal time per part while increasing thermal interaction or putting more inventory at risk.

Automation should be evaluated at transfer points. Automatic nesting, powder dosing or depowdering does not automatically release powder, verify channel cleanliness, dispose of deviations or accept the component. Lights-out production requires detection and controlled response for powder-delivery failure, recoater events, printhead or laser deviation, thermal excursion, interrupted build, unsafe containment state and failed recovery.

Economic comparisons must freeze annual volume and mix, material and powder-refresh rules, build utilisation, cooling assets, labour, ventilation, recovery yield, finishing, inspection, reject disposition, equipment availability and inventory cost. Virgin powder price or headline parts-per-build is not component cost. The comparator may be injection moulding, machining, material extrusion, vat photopolymerisation or no manufacture; it must deliver the same accepted state.

## 12. Occupational safety and containment

Polymer-PBF work includes handling fine powder, heated equipment, moving recoaters, lasers or intense radiation, jetted process fluids, compressed air, combustible dust potential and post-processing dust. Risks vary with polymer, additives, agents, particle distribution, temperature, equipment enclosure and tasks. A polymer label alone cannot establish an exposure profile.

NIOSH identifies powder inhalation and dermal exposure, fire and explosion from combustible materials, mechanical hazards and ergonomic risks as relevant additive-manufacturing concerns whose importance depends on technology, material and environment [26]. This supports task-based hazard assessment and the hierarchy of controls. It does not provide a process-specific safe concentration or prove that enclosure and filtration are effective in a particular cell.

Unpacking, sieving, compressed-air blow-off, blasting and vacuum recovery can suspend powder and place a combustible cloud near electrostatic, hot-surface, electrical, laser or mechanical ignition sources. A bounded study of one PA12 additive-manufacturing powder demonstrated explosibility and measured maximum explosion pressure, deflagration index and dispersed-cloud minimum ignition temperature [29]; its values are not transferable to another formulation, particle distribution or powder history. The dust-hazard assessment must therefore determine maximum explosion pressure (P<sub>max</sub>) and deflagration index (K<sub>st</sub>), minimum ignition energy (MIE) and minimum autoignition temperature of the dispersed dust cloud (MIT) for the actual powder states handled, including virgin powder, recovered powder, fines-enriched fractions and the production blend. ASTM E1226-19(2025), E2019-03(2025) and E1491-06(2025) provide corresponding test methods [30-32].

The preferred production design keeps powder and agents inside closed or contained transfers, captures dust at unpacking and depowdering, avoids uncontrolled compressed-air dispersion, and defines safe cleaning, spill, filter-change and waste procedures. The measured P<sub>max</sub> and K<sub>st</sub> must inform enclosure, confinement, deflagration-protection and equipment decisions; MIE must inform bonding, earthing and electrostatic or electrical ignition control; and MIT must inform hot-surface and thermal limits. These decisions belong in a facility-specific dust-hazard assessment under the applicable combustible-dust framework, such as NFPA 660:2025 [33], together with actual cloud concentration, ventilation, credible ignition sources, connected equipment and upset or cleaning tasks. A vacuum or dust collector is acceptable only when its design, location, filtration, bonding and explosion protection match the assessed powder; an ordinary shop vacuum or uncontrolled blow-off is not an equivalent control. Respiratory protection, when required, supplements rather than replaces engineering controls and needs a compliant programme.

Post-processing can dominate exposure. Blasting, brushing, tumbling, machining and internal-channel cleaning can release particles or finishing media. Agent containers, contaminated wipes and mixed powder may require separate chemical and waste controls. The qualification record should include ventilation state, enclosure interlocks, filter identity and service state, cleaning method, task location, operator training and the basis of any exposure assessment.

### 13. Qualification architecture and change control

ISO/ASTM 52920:2023 requires the process and production site to be controlled as a system [2]. For polymer PBF, the qualification boundary includes feedstock genealogy, conditioning, spreading, energy or agent delivery, thermal history, build layout, cooling, recovery, finishing, conditioning, measurement and disposition. The machine is one controlled element inside that boundary.

The process specification should identify commanded and measured states separately. It should control powder lot and blend; storage and exposure; machine and build unit; recoater or roller; layer strategy; laser and optics or fluids, printheads and lamps; calibration; bed and chamber temperatures; atmosphere where relevant; build-layout revision; cooling endpoint; unpacking; powder recovery; depowdering; finishing; conditioning; sampling; inspection and acceptance.

Change control must include powder supplier or formulation, colourant or filler, particle distribution, virgin/used blend rule, recovery equipment, sieve, storage, recoater, laser/optics, agent or fluid lot, printhead, lamp, sensor, firmware, build processor, nesting algorithm, layer thickness, thermal setpoints, cooling route, finishing, conditioning and measurement. A change can be called equivalent only when causal characteristics and accepted-component evidence remain within the validated boundary.

Table 3. Minimum industrial qualification record

| Record block                     | Minimum controlled content                                                                                                                              | Release question                                                                                                |
|----------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------|
| <b>Powder genealogy</b>          | Supplier/lot, formulation, virgin/recovered sources, exposure classes, tests, blend, storage and mass balance                                           | Was every build fed with powder inside the validated material state?                                            |
| <b>Layer formation</b>           | Delivery, recoater/roller identity and wear, layer setting, monitored spread events and disposition                                                     | Was a suitable powder layer formed in every critical region?                                                    |
| <b>Selective system</b>          | Laser/optics/scan or fluid/printhead/lamp state, calibrations, maintenance and deviations                                                               | Was selective input delivered rather than only commanded?                                                       |
| <b>Build and thermal history</b> | Geometry revision, orientation, nesting, protected zones, bed field, layer timing, cooling and transfer                                                 | Does the production build match the qualified spatial and thermal state?                                        |
| <b>Recovery and finishing</b>    | Cake condition, unpacking, depowdering access/evidence, surface treatment, machining and conditioning                                                   | Is the measured object in the declared delivered state and free of unacceptable powder?                         |
| <b>Safety and containment</b>    | Actual-powder Pmax, Kst, MIE and MIT basis; enclosure, ventilation, bonding/earthing, ignition controls, interlocks, dust-collection and cleaning state | Were build, recovery and finishing tasks performed inside the qualified containment and ignition-control state? |
| <b>Measurement</b>               | Location-linked coupons, dimensions, surface, porosity/internal evidence, properties, function and uncertainty                                          | Do tests address the component-critical failure modes?                                                          |
| <b>Acceptance and change</b>     | Part/build traceability, deviations, rework, rejects, powder disposition and equivalence decisions                                                      | Can every accepted component be linked to an unchanged qualified route?                                         |

### 14. Selection gate, limitations and conclusions

Selection starts with the conditioned delivered component. The gate is:

1. Define material, geometry, surface, dimensional, mechanical, cleanliness, functional and environmental acceptance.
2. Eliminate powders and architectures that cannot create a stable spread and selective-fusion window for the required formulation.
3. Verify build orientation, nesting, thermal extremes, edge state, minimum features, cooling and post-processing allowance.
4. Demonstrate that all internal powder can be removed and that removal can be verified at the required risk level.
5. Establish powder genealogy, reuse/refresh and contamination controls without relying on a universal percentage.
6. Qualify relevant orientations, locations, conditioned states and complete-cell transfers with measurement uncertainty.
7. Compare accepted-part throughput, yield and full factory cost against a declared alternative, or issue a no-go decision.

The evidence base is dominated by PA11 and PA12 and by defined commercial or research systems. This review does not provide universal powder specifications, process windows, refresh ratios, dimensional limits, property tables, machine rankings or cost multipliers. Manufacturer evidence is used only to describe SAF architecture. Recent geometry and process studies demonstrate bounded mechanisms, not general performance guarantees.

The following conclusions control industrial use:

1. Laser PBF/SLS, MJF, HSS and SAF share powder layering but create and control selective fusion differently.
2. Powder identity includes particle, thermal, storage and exposure history. Virgin-powder certification does not qualify a recovered blend.
3. A spread command is not a verified layer, and an energy or agent command is not the local thermal history.
4. Polymer coalescence, crystallisation, degradation and distortion are coupled to location, geometry, build layout and cooling.
5. No universal reuse fraction, refresh ratio, cycle count or melt-flow limit is valid across materials and machines.
6. Surrounding powder can support geometry while leaving an unacceptable internal channel that cannot be cleaned or inspected.
7. Porosity, surface, dimension and properties must be measured in representative locations, orientations and conditioned states.
8. Accepted components per complete cell cycle, including cooling, recovery, finishing, inspection and yield, is the relevant throughput measure.

9. Qualification must connect powder genealogy, layer formation, selective delivery, thermal history, recovery, measurement, acceptance and change control.

The correct result may be laser PBF, an agent-and-infrared route, another manufacturing process or no additive route. The engineering output is the traceable accepted component, not a full powder cake or a completed machine cycle.

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