

Electrically and Thermally Functional Nano/Micron Materials for Additive Manufacturing: Conductivity, ESD, EMI Shielding, Percolation, Interfaces, Anisotropy and Qualification

A State-Resolved Framework for Conductive, Dissipative, Shielding and Heat-Transport Functions

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Statement of Significance

Electrically or thermally functional additive-manufacturing feedstocks are often compared by a filler name and one favourable number. That practice is unsafe for engineering selection. Direct-current conductivity, electrostatic-dissipative behaviour, electromagnetic-interference shielding and heat transport are different functions. They require different specimens, boundary conditions, directions, frequencies, contacts, environments and acceptance evidence. A carbon-filled polymer can be adequate for charge decay yet unsuitable as a low-loss conductor. A material with measurable direct-current conductivity may provide poor shielding at the required frequency, or a porous shield may show a favourable mass-normalized value while failing at joints and apertures. A boron-nitride composite may preserve electrical insulation while conducting heat preferentially along deposited roads, leaving the required through-thickness path weak. This review establishes a state-resolved chain from functional requirement and raw-material identity through dispersion, percolation, printing, transformation, contact formation, ageing and device-level qualification. It compares carbon, conducting-polymer, metal and ceramic routes without creating a universal filler ranking. It treats the public 3Dresyns nano/micron portfolio only as a manufacturer-declared map of candidate families, not as independent proof of printability, safety or performance. The qualifying unit is the complete material–process–geometry–interface–test system in the state in which the component will be used.

Abstract

Nano- and micron-scale carbon, metal, conducting-polymer and ceramic phases can provide electrical conduction, controlled electrostatic dissipation, electromagnetic shielding or heat transport in additively manufactured components. The same constituent can also increase viscosity, cure attenuation, sedimentation, nozzle wear, agglomeration, porosity, contact resistance, anisotropy and occupational-control burden. This qualitative engineering review separates four functions that are frequently collapsed under the word *conductive*: direct- and alternating-current transport; electrostatic-discharge control; electromagnetic-interference shielding; and thermal conduction or diffusivity. For each function it identifies the measurable quantity, specimen and electrode or fixture, direction, conditioning, geometry, frequency or temperature domain, uncertainty and product-level evidence required for qualification. The review explains electrical percolation, tunnelling and contact-limited networks; distinguishes a dispersed filler population from a connected transport network; and examines how shear, toolpath, layer interfaces, cure shrinkage, porosity and post-processing change the as-tested state. Retained composites based on carbon black, carbon nanotubes, graphene-related materials, graphite, conducting polymers, metallic particles or nanowires, conductive oxides and thermally conductive ceramics are compared with printed metal inks, selective metallization, infiltration and conversion routes. Process sections address material extrusion, direct ink writing, inkjet and material jetting, vat photopolymerisation and powder-bed composites. Primary studies are used as bounded demonstrations of mechanisms rather than transferable recipes. An applied example compares three routes for an electronics fixture that requires grounded electrostatic dissipation, local electrical insulation and heat removal, and shows why the functions should be allocated to different material zones when a single composite cannot close all requirements. The review concludes that functional qualification must preserve the causal chain from lot and formulation through local network, printed direction, contact architecture, ageing and the accepted device. No loading, conductivity, surface resistance, shielding effectiveness or thermal conductivity is universal outside that chain.

Keywords: *additive manufacturing; electrical conductivity; electrostatic discharge; ESD; electromagnetic-interference shielding; EMI; thermal conductivity; thermal diffusivity; percolation; tunnelling; carbon nanotube; graphene; graphite; PEDOT:PSS; silver ink; boron nitride; anisotropy; qualification*

1. Purpose, scope and governing distinctions

This paper makes functional nano/micron materials selectable as industrial systems rather than as catalogue claims. It has seven objectives. First, it separates electrical conduction, electrostatic control, electromagnetic shielding and heat transport at the requirement level. Second, it connects filler state, matrix, interfaces and printed architecture to the transport path actually created. Third, it compares retained composites, directly printed functional phases and post-print conversion or metallization. Fourth, it defines process-specific failure gates before a feedstock enters production. Fifth, it establishes measurement records that prevent a favourable coupon from being detached from direction, geometry and conditioning. Sixth, it demonstrates the framework with an industrial route-selection example. Seventh, it defines the minimum genealogy and change-control evidence required for qualification.

Corpus-level additive-manufacturing technology selection is inherited from ER-139; this review owns only electrical conduction, electrostatic-control, electromagnetic-shielding and thermal-transport evidence for applying that framework.

Dielectric, ferroelectric, piezoelectric and magnetic functions are owned by ER-158, and optical, photonic, luminescent and radiation functions by ER-159; this review does not reopen those domains.

ISO/ASTM 52900 supplies the base vocabulary and process categories for additive manufacturing (AM) [1]. ISO/ASTM 52920 addresses industrial process and production-site qualification [2], while ISO/ASTM 52927 organizes main AM characteristics and corresponding test methods [3]. These standards support the manufacturing framework, but a process category does not specify a functional network. A material-extrusion coupon and a direct-ink-written trace can both contain carbon nanotubes (CNTs) yet differ in matrix fraction, orientation, voids, contact geometry, thermal history and measurement method. Their results are not interchangeable.

Four functions are therefore kept separate throughout this review. **Electrical conduction** concerns charge transport under a declared direct-current (DC) or alternating-current (AC) field and is reported as resistance, conductance, resistivity, conductivity or impedance with an explicit geometry and direction. **Electrostatic control** concerns charge generation, transfer, decay and safe connection to a reference potential in a defined use environment. **Electromagnetic-interference (EMI) shielding** concerns attenuation of electromagnetic energy over a specified frequency band, field regime, polarization, incidence and enclosure geometry. **Thermal transport** concerns heat flow and transient response, requiring conductivity, diffusivity, density, heat capacity, interface resistance and direction to be distinguished.

Those distinctions prevent three category errors. A low electrical resistance is not automatically an electrostatic-safe design because grounding, tribocharging, isolated conductors and personnel or equipment interfaces can dominate. DC conductivity is not shielding effectiveness because EMI response depends on frequency, permittivity, permeability, thickness, apertures and measurement geometry. Filler thermal conductivity is not composite or device heat removal because interfaces, orientation, porosity, contact pressure and convection can control the temperature rise.

The scope includes component-scale 2D traces, coatings and films; retained 3D polymer composites; powder-bed polymer composites; direct-ink-written or jetted functional structures; conducting-polymer systems; metal-particle, precursor and nanowire inks; selectively metallized polymer components; and thermally conductive ceramic-filled systems. Carbon black, CNTs, graphene-related materials, graphite, PEDOT:PSS, silver and copper systems, conductive oxides, boron nitride (BN), aluminium nitride, alumina, magnesium oxide and diamond-like fillers are representative families. ISO/TS 80004-13 is used to avoid treating *graphene* as a single, self-defining material [36].

The paper excludes concrete, cement, geopolymers, regolith and macroscopic construction deposition. It does not prescribe universal filler loadings, percolation thresholds, resistivity classes, shielding targets, thermal conductivities, safety controls or device acceptance limits. Those values belong to a written application, standard, specimen, population and uncertainty. The 3Dresyns public nano/micron page maps a broad candidate space [35]; it is not used as independent evidence that a listed material will disperse, print, remain safe or deliver a specified function.

2. Start with the function, not the filler

A functional-material project should begin with a measurable product requirement. “Conductive housing” is not sufficient. The requirement states what must move or be attenuated, along which path, over what distance and time, in which direction and state, under what environment, and with what allowable variation. The component may need a grounded dissipative surface, an electrically insulating heat path, a low-resistance current path, an RF shield or several spatially separated functions. Those are different architectures.

For DC conduction, the requirement identifies current and voltage ranges, permissible voltage drop or Joule heating, conductor geometry, contact system, direction, temperature, humidity, strain and life. A bulk conductivity value cannot qualify a printed connector when the dominant resistance lies at an insert, plated transition or layer boundary. For AC or impedance-controlled function, the frequency range, phase response, parasitic capacitance and inductance, dielectric environment and connector de-embedding method are part of the requirement.

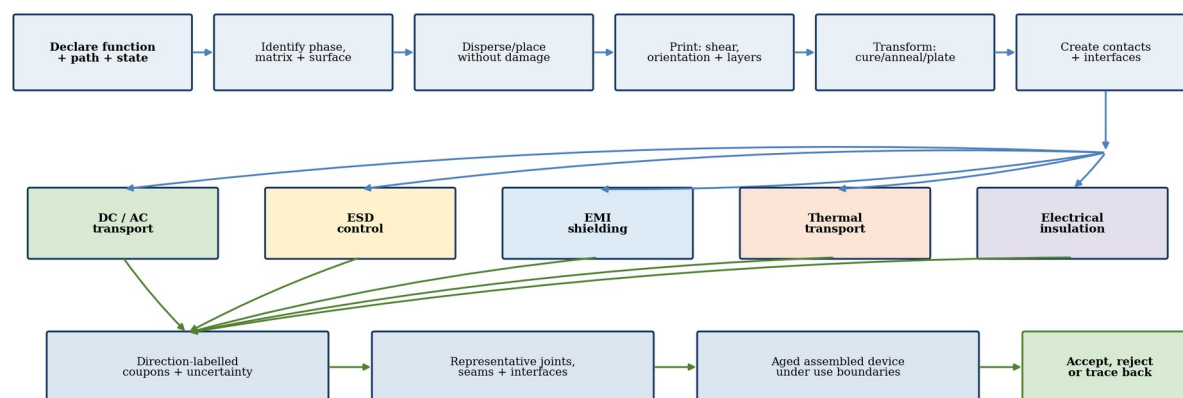
For electrostatic-discharge (ESD) control, the requirement identifies the protected items, charging mechanisms, groundable points, decay or resistance path, operating relative humidity, contamination and cleaning, personnel interaction and verification plan. IEC 61340-5-1:2024 provides general requirements for an ESD control programme for handling susceptible electronic items [5]. IEC 61340-2-3:2016 provides methods for resistance and resistivity measurements of solid materials used to avoid electrostatic charge accumulation [4]. Neither permits a generic commercial label to replace measurement on the final printed construction.

For EMI shielding, the requirement names the source and victim, frequency band, near- or far-field regime, electric or magnetic field dominance, polarization, incidence, enclosure seams, ventilation openings, cable penetrations, grounding or bonding and allowable emissions or susceptibility. ASTM D4935-18(2026) addresses planar-material shielding effectiveness under specified far-field conditions over a limited frequency range [7]. Its result is not automatically the performance of a three-dimensional enclosure, and it does not cover cables or connectors. A material coupon can screen a route; the assembled product closes the requirement.

For heat transport, the requirement identifies heat generation, allowable junction or surface temperature, ambient and coolant conditions, direction of heat flow, contact pressure, interface material, convection or radiation boundary and duty cycle. ISO 22007-1:2024 explains that different thermal methods suit different material states and forms [8]. ISO 22007-2:2022 addresses the transient plane heat source method [9], ISO 22007-4:2024 addresses light-flash determination [10], and ASTM D5470-17(2024) addresses thermal impedance of thermally conductive electrical-insulation materials [11]. A method is selected because its assumptions fit the specimen and decision, not because it yields the largest number.

Table 1. Four functions that must not share one acceptance number

Function	Primary output	Mandatory test descriptors	Product-level closure	Invalid substitution
DC/AC electrical transport	Resistance, resistivity, conductivity or complex impedance	Specimen dimensions; two- or four-terminal arrangement; electrode material and preparation; current/voltage; frequency; direction; temperature; humidity; strain; uncertainty	Voltage drop, power loss, signal integrity or device response through actual contacts and paths	Filler conductivity, colour or continuity beeper alone
Electrostatic control	Surface/volume resistance or resistivity, charge decay and system-to-ground performance	Standard and electrode geometry; conditioning humidity/time; applied voltage; electrification mode; ground connection; cleaning and wear state	ESD-control programme verification on the installed item and use scenario	Calling any conductive composite “ESD safe”
EMI shielding	Shielding effectiveness and, where valid, reflection/absorption or scattering parameters	Frequency band; near/far field; polarization; incidence; specimen thickness; density; aperture/fixture; reference; dynamic range; uncertainty	Enclosure-, seam-, aperture-, cable- and bond-level emissions/susceptibility result	DC conductivity or one peak dB value
Thermal transport	Thermal conductivity, diffusivity, impedance or contact resistance	Method; direction; specimen size/density; temperature; heat flux; contact pressure; surface; heat capacity; coating; uncertainty	Temperature and stability of the actual device under duty cycle and boundary conditions	Raw-filler conductivity or infrared colour image alone



A result is valid only for the same material state, path, direction, contact, environment and method.

Figure 1. State-resolved functional chain from requirement to accepted device.

The chain is deliberately bidirectional. A device failure is not corrected first by adding more filler. It is traced backward through contact, geometry, local network, printing, formulation and raw-material state. A formulation change is not accepted because its coupon improved; it moves forward through processability, ageing, safety and device tests.

3. Functional material families and route states

No filler family is intrinsically best. Each offers a transport mechanism coupled to a processing penalty and a state boundary. Carbon black can form a relatively isotropic population at small length scale but can demand substantial surface wetting and alter viscosity or cure. CNTs offer high aspect ratio and potential network formation at lower volume fraction, while bundles, damage, filtration, alignment and occupational exposure can dominate. Graphene-related platelets and graphite can provide electrical and in-plane thermal pathways, but platelet orientation can create large through-plane penalties. ISO/TS 80004-13 reinforces that layer number, lateral dimension, thickness, defect state and functionalization belong to identity [36].

Conducting polymers such as PEDOT:PSS are not merely polymer matrices containing conductive powder. Their electronic and, in wet states, ionic transport depend on composition, dopant or solvent history, phase separation, water, annealing and morphology. Yuk and co-workers demonstrated a concentrated, printable PEDOT:PSS route whose conductivity and mechanics changed between dry and swollen states [26]. Hill and co-workers later showed that ink formulation, lateral phase separation, print orientation, bed temperature and nozzle diameter could dominate the conductivity of printed PEDOT:PSS [27]. These are strong demonstrations that process-created morphology is part of the conductor; neither paper establishes a universal PEDOT:PSS recipe.

Metallic particles and nanowires can provide low-resistance networks after solvent removal, ligand decomposition, sintering or welding. Their initial high intrinsic conductivity does not remove junction resistance or oxide barriers. Fine silver can offer favourable processing temperatures, but cost, migration, sulphur exposure, adhesion and occupational controls remain relevant. Copper offers cost and conductivity advantages while creating oxidation and process-atmosphere challenges. Metal oxides can be conductive, semiconductive or insulating depending on composition, stoichiometry and doping; the name *oxide* says little about the intended function.

Particle-free or precursor inks change the route. Walker and Lewis demonstrated a reactive silver ink in which conductive silver formed after patterning and mild thermal treatment [30]. Skylar-Scott and co-workers coupled direct ink writing with local laser processing of metal inks [31]. These routes avoid some particle-delivery constraints but add chemical conversion, shrinkage, gas release, substrate compatibility and local energy control. A printed line before conversion is not the accepted conductor.

Thermally conductive ceramics such as BN, aluminium nitride, alumina and magnesium oxide can improve heat transport while retaining electrical insulation. Platelet or fibre anisotropy can be exploited only if the deposited orientation connects the actual heat source and sink. Quill and co-workers showed that BN-filled ABS printed by material extrusion differed from injection-moulded material and that infill orientation affected properties [21]. Bagatella and co-workers demonstrated printed BN-filled heat-sink concepts and explicitly measured both thermal and electrical behaviour [24]. These studies support the route, but their loading, polymer, direction and geometry cannot be detached from the reported result.

Table 2. Material-family opportunities, coupled penalties and state gates

Family	Transport opportunity	Processing and interface risks	State that must be qualified	Early no-go gate
Carbon black	Dense contact population; dissipative or conductive composites	High surface demand, viscosity, cure attenuation, contamination, brittle behaviour at loading	Printed composite after full conditioning and contact preparation	Required network cannot be reached without losing printability or mechanics
CNTs and carbon nanofibres	High-aspect-ratio electrical network; sensing; possible EMI and thermal contribution	Bundles, breakage, alignment, filter retention, exposure, contact variability	Post-mixing length/bundle state and direction-resolved printed network	Uncontrolled nanoform or exposure; network varies across hold time or toolpath
Graphene-related materials and graphite	Electrical and in-plane thermal paths; EMI loss; printable platelets	Terminology ambiguity, restacking, platelet alignment, through-plane resistance, cure scattering	Identified nanoform/grade and local orientation in final geometry	Filler identity or direction is unspecified; required through-plane path remains open
PEDOT:PSS and other conducting polymers	Soft or conformal electronic paths; tunable dry/wet behaviour	Solvent/additive sensitivity, phase separation, humidity, electrochemical drift, low structural yield	Exact dry, humid, swollen or biased state with electrode interface	Conductivity is reported in a different state from intended use
Silver, copper and metallic particles/nanowires	Low-resistance traces, heaters, antennas and metallization seeds	Oxide/ligand films, sintering, junctions, migration, fatigue, adhesion, cost and exposure	Converted metal network plus substrate/contact and ageing	Substrate cannot tolerate conversion or joints dominate resistance
Conductive oxides	Transparent, resistive, sensor or high-temperature functions in selected chemistries	Stoichiometry, dopant, brittle network, high consolidation temperature, contact barriers	Final phase, density, surface and electrode system	Required phase or contact cannot be produced within substrate/process limits
BN, AlN, alumina, MgO and related thermal ceramics	Heat transport with electrical insulation	High loading, abrasion, viscosity, voids, platelet orientation, interface resistance	Direction-resolved composite and actual heat-transfer interface	Thermal gain is in the wrong direction or insulation/breakdown is lost
Post-print metal coating or infiltration	Function concentrated at surface/path; polymer geometry with metal transport	Activation, coverage in recesses, adhesion, thickness variation, bath chemistry, seams and fatigue	Continuous coating/infiltrant after environmental and handling exposure	Critical internal surfaces cannot be accessed, inspected or repaired

4. Electrical transport: percolation is a process-created state

An insulating matrix containing conductive particles does not become conductive in proportion to filler mass. Transport begins when a population of connected or sufficiently close conductive entities spans the measured path. Classical percolation theory describes the emergence of long-range connectivity and its scaling near a threshold [13]. Excluded-volume treatments show that particle geometry and the volume excluded by individual particles can govern the onset of percolation [14]. These theories explain why a sharp transition may occur, but they do not supply a universal threshold for a commercial filler.

The threshold depends on volume fraction, aspect ratio, size distribution, aggregation, matrix wetting, excluded volume, processing orientation and the criterion used to define a connection. Reporting only weight fraction obscures density differences. A small mass of CNT can represent a different occupied volume and contact topology from the same mass of silver or graphite. A hybrid system can fill geometric gaps or, equally, separate an existing network. “Synergy” should therefore be reserved for a comparison with defined single-filler controls, equal total volume, matched processing and uncertainty.

Dispersion has two competing meanings. Better distribution can remove large agglomerates, improve print consistency and expose surface. It can also separate conductive clusters and raise resistance if the original agglomerates carried the spanning network. The target is not maximum deagglomeration; it is a controlled population that prints repeatably and produces the required local network without unacceptable defects or exposure. Mixing energy, temperature, time, sequence, surfactant and contamination belong to the batch record.

High-aspect-ratio fillers can bend, shorten and align. CNT breakage during compounding reduces effective aspect ratio. Nozzle flow can align fibres along the road, favouring road-direction transport while reducing transverse contacts. Platelets can lie in the deposition plane, improving in-plane conduction but requiring many high-resistance junctions through thickness. The same orientation can be advantageous for a planar heater and disqualifying for a vertical current collector.

Gnanasekaran and co-workers compared CNT/PBT and graphene/PBT before and after fused-deposition modelling and observed material- and process-specific electrical behaviour [15]. Their result is valuable because it demonstrates that printing can alter the network and that CNT and graphene systems need not respond alike. It does not justify a general statement that one filler always outperforms the other. The comparison remains bounded to the selected grades, polybutylene terephthalate matrix, formulation and equipment.

Leigh and co-workers printed carbon-black/polycaprolactone structures and demonstrated sensor functions [16]. Their work also exposed directionality and the importance of the electrical contact arrangement. A printed sensor is a network, geometry, electrode and mechanical transfer system; its response cannot be inferred from a filament resistance alone.

Contact resistance deserves an explicit budget. Two-terminal resistance contains the specimen, lead, electrode, spreading and interface contributions. Four-terminal methods separate voltage sensing from current injection over the selected region and are valuable when contact resistance is not negligible. Smits’ treatment of the four-point probe remains foundational for sheet-resistance measurement and geometric correction [12]. Yet a four-point coupon can hide the very contact that controls the product. Development should therefore use both an intrinsic-material configuration and a product-representative joint configuration.

For a prismatic specimen, converting resistance to resistivity assumes a known, uniform current cross-section and length. Printed roads contain voids, bead boundaries, skins and local filler gradients. A nominal CAD cross-section is not necessarily the conductive cross-section. Dimensional metrology, density, microscopy and, when warranted, electrical tomography or sectioned mapping are needed to interpret the result. When geometry is irregular or current spreads from a small electrode, reporting raw resistance with a drawing may be more honest than an unjustified bulk conductivity.

AC response adds capacitance, inductance, polarization and frequency-dependent hopping or interface effects. The material may show low-frequency conduction and high-frequency dielectric loss through different mechanisms. Equivalent-circuit fitting is not unique unless the circuit is physically justified and tested across relevant conditions. The unprocessed impedance spectrum, fixture correction, electrode area, frequency window and fit residuals should remain in the record.

5. ESD control: a system property, not a conductivity label

Electrostatic safety is concerned with controlled charging and discharge in an operating system. A printed polymer may be labelled antistatic, dissipative or conductive by a supplier, but the industrial decision requires the relevant resistance, decay and ground-path behaviour after the actual print, cure, conditioning, cleaning, wear and assembly. IEC 61340-2-3 defines resistance and resistivity test methods for relevant solid materials [4]. IEC 61340-5-1:2024 defines programme-level requirements for protecting susceptible electronic items [5]. The test and programme roles should not be collapsed.

Humidity is often a controlling variable. Surface conduction can rise through adsorbed moisture or ionic contamination. A coupon that passes after high-humidity conditioning may fail in a dry assembly area; a hygroscopic dissipative system may drift after drying, cleaning or sealing. Conditioning temperature, relative humidity, duration and time between conditioning and measurement must be reported. The lowest expected humidity and the contamination state after realistic cleaning deserve explicit verification.

Geometry and grounding matter as much as nominal material resistance. A tray may contain conductive roads that do not intersect the designated ground point. A printed insert may isolate a metal fastener with a polymer-rich skin. A coating can crack around a snap fit. A fixture can accumulate charge on an electrically isolated tool or label even when its base material is dissipative. The system map identifies every chargeable surface, conductive insert, interface, operator contact and path to reference ground.

The desired resistance is not always “as low as possible.” Rapid discharge can create a damaging event; a controlled dissipative path can limit current while preventing charge accumulation. The correct range and decay behaviour come from the protected device, ESD-control plan and applicable standard. A formulation should not be optimized solely for minimum resistivity if it increases brittleness, particle shedding, electrical noise or the probability of an isolated conductive island.

Triboelectric charging must be tested with representative contact and separation. Material pairs, surface roughness, pressure, speed, cleanliness and humidity change the sign and magnitude of charge. A static voltage reading on an untouched coupon does not represent repeated part removal. For bins, nests or end-of-arm tooling, the use cycle is itself a test method: load, move, contact, separate, ground, clean and repeat while monitoring the relevant surface and device.

Ageing mechanisms include polymer relaxation, moisture exchange, additive migration, surfactant bloom, abrasion, carbon-network rearrangement, cracking, chemical cleaning and thermal cycling. Resistance can change reversibly with temperature or strain and irreversibly with damage. Acceptance therefore includes initial distribution, environmental preconditioning, use cycling and recovery, with limits on both mean and tails. A few passing coupons cannot establish the probability of an extreme high-resistance region across a large printed surface.

6. EMI shielding: frequency, field and enclosure define the result

Shielding effectiveness is a logarithmic comparison of electromagnetic power or field with and without a shield under a defined test configuration. It is not an intrinsic scalar independent of thickness and fixture. Reflection, absorption and multiple interactions can contribute, but decomposition depends on the measurement and model. A statement such as “absorption-dominated” should identify how scattering parameters were converted, the specimen thickness and the frequency band.

ASTM D4935-18(2026) provides a controlled method for planar materials under normal-incidence far-field conditions and specifies a nominal 30 MHz to 1.5 GHz range for its described holder [7]. The standard itself identifies limitations. Results from waveguide, coaxial, free-space, reverberation-chamber and near-field fixtures can answer different questions. A result in X-band cannot be used as evidence for low-frequency magnetic shielding, and a planar coupon cannot represent enclosure seams, cable penetrations or ventilation apertures.

Electrical conductivity supports reflection and ohmic loss, while permittivity, permeability, thickness, skin depth, porosity and architecture affect coupling and attenuation. Higher DC conductivity does not guarantee better total shielding in every geometry. A highly reflecting shield can create system-level coupling elsewhere. A porous, impedance-graded or magnetic architecture may increase absorption in a selected band. These are design choices, not a universal hierarchy.

Guan and co-workers used magnetically assisted direct ink writing to control graphite-microplatelet orientation and macrostructure, then measured EMI and heat-dissipation behaviour in a defined electronic-packaging context [17]. The study demonstrates that micro- and macrostructure can modulate function independently of nominal composition. Its reported shielding values remain tied to the ink, printed architecture, specimen thickness and tested frequency ranges.

Xu and co-workers studied a three-dimensionally printed CNT/PLA system for EMI shielding [18]. Shi and co-workers created direct-ink-written carbon-based conformal shielding modules and evaluated both shielding and thermal behaviour [19]. Xiong and co-workers produced PA12/CNT composites with a segregated network through selective laser sintering [20]. Together these papers show at least

three distinct causal routes: a retained melt composite, a formulated porous carbon ink and a powder-bed segregated network. Their values should not be ranked without normalizing frequency, thickness, density, porosity, test fixture, mechanical state and application boundary.

Mass-normalized or thickness-normalized shielding metrics can help compare lightweight concepts, but they can also obscure absolute failure. An enclosure must still meet its attenuation requirement. Density reduction that increases specific shielding may introduce openings, weak walls, moisture uptake or poor thermal contact. Both absolute and normalized values should be reported, with the normalization formula and measured density.

The final shield is an assembly. Surface coating continuity around edges, overlap at seams, fastener spacing, gasket compression, conductive adhesive, paint thickness, substrate cracks and galvanic compatibility affect current paths. A material coupon is followed by subassembly transfer-impedance or leakage testing and then by product emissions and immunity tests appropriate to the equipment. If the selected material only passes when every aperture is absent, it is not qualified for a ventilated enclosure.

7. Thermal transport: conductivity, diffusivity and impedance answer different questions

Thermal conductivity relates heat flux to a temperature gradient under stated assumptions. Thermal diffusivity describes how rapidly a temperature disturbance propagates and depends on conductivity, density and specific heat capacity. Thermal impedance includes thickness and can include interfaces. Contact resistance can dominate a thin, highly conductive layer. These quantities cannot be exchanged by label or thermography alone.

ISO 22007-1:2024 provides general principles and emphasizes method selection for the material state and form [8]. The transient plane heat source method in ISO 22007-2:2022 and the light-flash method in ISO 22007-4:2024 impose different specimen and model requirements [9,10]. ASTM D5470-17(2024) is especially relevant to thermal-interface and electrical-insulation materials because it separates, through multiple thicknesses when feasible, apparent bulk behaviour from the combined contact resistance [11]. The method, direction, temperature, pressure and surface preparation remain inseparable from the number.

Heat transport in filled polymers is limited by more than filler intrinsic conductivity. Polymer–filler and filler–filler thermal boundary resistance, poor wetting, oxide or ligand shells, phonon mismatch, voids and imperfect contacts interrupt the path. A high-aspect-ratio platelet can conduct strongly along its plane while contributing little across its thickness. If extrusion aligns platelets parallel to the build plane, an in-plane coupon may improve while a heat source beneath the wall remains poorly connected to the external sink.

Quill and co-workers compared printed and injection-moulded BN/ABS composites and varied infill orientation [21]. Bagatella and co-workers studied unmodified BN in printable polymer composites for flexible thermal-management concepts [22], examined nano- and micro-BN/epoxy trade-offs between thermal transport and printability [23], and demonstrated electrically insulating printed heat-sink structures from BN-filled thermoplastic systems [24]. The combined evidence shows why a filler property cannot be promoted directly to a device claim: loading, platelet size, formulation rheology, alignment, density, polymer state and part topology all contribute.

Thermal networks need not exhibit the same percolation threshold as electrical networks. Electrical tunnelling can bridge nanometre gaps across an insulating polymer, whereas heat transfer across an interface remains penalized by boundary resistance. A carbon composite may become electrically conductive at a loading that gives modest thermal improvement. Conversely, a high-loading BN composite can improve heat transport while remaining electrically insulating. Calling both behaviours *percolation* without the measured response and fitted domain invites a false analogy.

Thermography is valuable for mapping assembled temperature fields but depends on emissivity, reflected radiation, viewing angle, calibration, spatial resolution and transient boundary conditions. A dark carbon-filled surface and a light ceramic-filled surface can appear different even at the same true temperature if emissivity is not controlled. Contact sensors, calibrated coatings, energy balance and repeated duty cycles should support the interpretation.

At device level, topology and convection can outweigh bulk conductivity. Thin fins printed in a favourable material can fail if bead interfaces block heat near the base, if warpage reduces mounting contact or if pressure deforms the interface. Conversely, a moderate-conductivity material can perform acceptably when geometry increases surface area and the heat path is short. Qualification therefore measures source temperature, sink temperature, ambient, power, contact pressure, airflow and orientation on the assembled device.

8. Dispersion, interfaces and the difference between distribution and connection

A functional feedstock requires two maps: where the constituent is and how it connects. Uniform concentration does not guarantee a connected network, and a connected network can coexist with local agglomerates. Microscopy at one magnification is insufficient. Low magnification detects gradients and voids; intermediate magnification detects road and layer boundaries; high magnification resolves bundles, platelets, junctions and interphases. Quantitative orientation, composition or network analysis should use a declared sampling plan.

Wetting determines whether matrix separates particles, whether a coating covers a metal junction and whether voids remain. Dispersants can lower viscosity and stabilize a suspension while leaving an electrically or thermally resistive layer at contacts. Coupling agents can improve mechanical adhesion but interrupt tunnelling. Solvents can reorganize conducting polymers. A formulation therefore balances print stability, function and ageing; no additive is functionally neutral.

Deagglomeration energy and sequence matter. Carbon nanomaterials can be damaged or shortened. Metallic nanowires can break. Platelet lateral dimensions can fall. Ceramic coatings can abrade from a core. Excessive sonication can heat or contaminate the batch; inadequate mixing can leave persistent clusters. The batch record should include equipment, geometry, mass, sequence, speed or power, duration, temperature and hold time, together with before/after evidence for the functional entity.

Sedimentation and flotation create time-dependent networks. A vat or cartridge can print early layers at one concentration and later layers at another. A recirculating jetting system can selectively retain large entities in filters. A nozzle can act as a classifier. A melt can exhibit filler migration or skin–core structure. Top, middle, bottom, early-build and late-build coupons should be compared whenever residence time is comparable to the instability timescale.

Cure couples optics and transport. Carbon and metal fillers can absorb or scatter the exposure wavelength, reducing cure depth. Higher exposure can increase conversion while overheating, distorting or damaging the functional phase. Shrinkage can bring particles closer and improve conduction, or it can crack a fragile network and debond interfaces. Photoinitiator, inhibitor, oxygen and filler surface can alter cure kinetics. The cured network must be measured after the complete wash and post-cure, not inferred from liquid dispersion.

Porosity can either interrupt conduction or form a deliberate EMI architecture. Uncontrolled voids increase electrical and thermal path tortuosity and reduce mechanical integrity. Designed pores can extend electromagnetic propagation paths or reduce mass. The distinction is intent plus evidence: pore size, connectivity, location, repeatability and structural effect must be quantified. A favourable shielding result does not retroactively make random defects a design feature.

9. Material extrusion and powder-bed fusion composites

Material extrusion imposes at least two orientation events: filament manufacture and part deposition. Compounding aligns or breaks fillers and establishes the filament skin–core structure. Passage through the print nozzle realigns the melt, after which fountain flow, cooling and road contact determine the local network. The deposited road can have high longitudinal conduction, lower transverse conduction and still lower build-direction conduction. A single XY coupon is therefore inadequate.

High filler loading increases melt viscosity, pressure and drive force and can reduce inter-road diffusion. A formulation can show improved within-road conductivity while producing poorer part-level conductivity because road welding deteriorates. Abrasive ceramic or carbon fillers wear the nozzle, changing diameter, flow, temperature field and contamination. Nozzle identity and cumulative service belong to change control.

Road geometry and skin state alter electrical contacts. A polymer-rich surface created during extrusion can insulate adjacent roads or metal terminals. Machining, sanding, solvent activation, conductive adhesive, thermal staking or plated inserts can reduce contact resistance, but each creates a new manufacturing state. The product drawing should specify contact preparation and inspectable area rather than relying on pressure from an unspecified fastener.

Gnanasekaran et al. [15] and Leigh et al. [16] provide bounded evidence for electrically functional extrusion systems. Quill et al. [21] and Bagatella et al. [24] provide bounded evidence for thermally functional, electrically insulating extrusion systems. Their deeper common lesson is that deposition orientation and final geometry determine which intrinsic filler direction is useful.

Polymer powder-bed fusion can preserve or create segregated conductive networks around powder particles. Xiong and co-workers demonstrated a PA12/CNT route in which coating and selective laser sintering produced a three-dimensional segregated network [20]. The opportunity is efficient network formation; the coupled risks include coating uniformity, airborne nanoform, powder reuse, thermal history, fusion-window change and concentration segregation. Reused powder is not automatically equivalent to virgin powder.

Laser absorption changes with filler. Carbon can increase energy coupling, narrow the process window and change thermal degradation. Conductive fillers can alter bed temperature distribution. The build position, refresh ratio, powder ageing and local density need correlation with function. A powder that spreads successfully but yields a drifting network across reuse cycles is not production-qualified.

10. Direct ink writing, inkjet, material jetting and vat photopolymerisation

Direct ink writing (DIW) can place a concentrated functional ink along designed paths and can deliberately orient anisotropic constituents. Printability requires flow through the nozzle and shape retention after deposition. Conductivity requires preserved or developed contacts after drying or conversion. Those requirements compete: polymeric binders and rheology modifiers stabilize shape but can electrically and thermally insulate the functional phase.

Yuk et al. [26], Hill et al. [27] and Oh et al. [25] demonstrate different PEDOT:PSS formulation strategies, state transitions and device contexts. Their values cannot be pooled because concentration, additives, post-treatment, humidity, geometry and electrode configuration differ. They do establish a robust principle: conductivity is created by formulation and post-print morphology, not inherited from the commercial dispersion.

DIW of graphite/CNT systems can couple rheology, filler ratio, orientation, porosity and EMI response. Guan et al. [17] and Shi et al. [19] show that designed architecture can participate in shielding and heat dissipation. The industrial translation requires ink ageing, nozzle-to-nozzle equivalence, dimensional variability, batch mixing and assembled-interface tests beyond proof-of-concept structures.

Inkjet and material jetting place small droplets and impose strict limits on viscosity, surface tension, particle-to-nozzle ratio, filtration and drying. Coffee-ring flow, substrate wetting and droplet coalescence can segregate filler across a trace. Multiple passes can crack or trap solvent. A nominal line width does not reveal its conductive cross-section. Drop spacing, waveform, meniscus history, cartridge temperature and nozzle health belong to the process record.

Metal-particle inks require ligand removal and neck growth. Reactive or precursor inks form the conducting phase during drying or annealing. Walker and Lewis [30] showed that particle-free chemistry can enable fine delivery and high conductivity after transformation. Skylar-Scott et al. [31] showed that localized laser treatment can integrate deposition and conversion. In both cases, the accepted object is the converted metal architecture. Residual precursor, porosity, substrate damage and feature-to-feature variability remain qualification questions.

Vat photopolymerisation offers fine geometry but couples the functional phase to optical cure. Carbon, metal or high-index ceramic fillers can change penetration and lateral scattering. Settling changes layer composition, and repeated recoating changes residence history. The cured polymer can separate particles at junctions. Post-cure can alter shrinkage, network contact and temperature. A resin that cures a small dark coupon is not automatically scalable to a deep vat, long build or internal channel.

Conductive photopolymer composites often trade conductivity against cure depth, viscosity and mechanical performance. Rather than forcing a bulk conductive resin to carry large current, a hybrid route can print insulating geometry and add conductive traces, inserts or coatings where required. The allocation of function to a smaller volume can reduce filler, exposure and process penalties.

11. Post-print conversion, metallization and hybrid architectures

Post-print metallization separates geometric manufacture from high-conductivity formation. A polymer can provide shape and low mass; an electroless, electroplated, sprayed, vapor-deposited or printed metal can provide the functional path. This architecture is attractive when bulk filler would compromise printability or when shielding and conduction are primarily surface functions.

The substrate must first present an activatable, clean and mechanically stable surface. Layer lines, pores and residual uncured material can cause nonuniform nucleation. Deep recesses, blind channels and lattice interiors may be inaccessible to cleaning, activation, bath flow and inspection. Surface roughness can improve mechanical keying while increasing local thickness variation. Coating thickness is therefore mapped around edges, corners, holes and shield seams rather than measured only on an external face.

Sharifi and co-workers demonstrated direct electroless copper plating on selected metal-infused printed polymer parts using a defined surface-exposure and bath route [28]. The study demonstrates feasibility and also illustrates that the filled polymer, surface preparation and plating bath form one system. It does not establish that every copper-filled filament will plate directly or that internal coverage will be complete.

Ahn and co-workers demonstrated omnidirectional printing of metallic microarchitectures from concentrated inks [29]. Directly printed metal and plated polymer are different routes. The former puts conversion shrinkage and structural integrity into the printed feature; the latter puts adhesion and coating continuity at the substrate surface. A route comparison should include resistance per accepted path, minimum robust feature, process yield, repairability, fatigue, chemical burden and access.

Infiltration can fill an intentionally porous printed preform with metal or another conductive phase. It can create three-dimensional networks beyond a surface coating, but introduces wetting, capillary access, trapped gas, reaction, incomplete fill and dimensional change. Pyrolysis can convert a polymeric precursor to carbon but creates mass loss, shrinkage, cracking and atmosphere dependence. Sintering can turn a particle-rich green feature into metal or conductive ceramic but requires binder removal and controlled densification. Each transformation receives a distinct part identity.

Hybrid architectures are often more rational than one universal composite. An electrically insulating BN-filled heat spreader can sit beside a carbon-filled grounded body, with plated copper only at current-carrying contacts and a gasket at the EMI seam. Additive manufacturing can place these zones, but interfaces then become first-class design features. The qualification plan must include adhesion, electrical isolation, thermal contact, dimensional tolerance and repair at every material transition.

12. Measurement architecture and uncertainty

Measurement begins with a drawing. The record identifies specimen geometry, print orientation, build position, road or layer pattern, skin and infill, post-processing, conditioning, electrode or thermal-contact area and measurement direction. A result without this drawing is incomplete. Replicates should span independent feedstock batches, builds and positions rather than repeated readings on one coupon alone.

For electrical transport, current–voltage linearity is checked over the intended range. Joule heating can lower or raise resistance and create apparent nonlinearity. Two-terminal and four-terminal results are compared when contacts may matter. Surface and volume paths are isolated using guarded fixtures when appropriate; IEC 62631-3-1:2023 provides a DC framework for volume resistance and resistivity of solid insulating materials [6]. Printed conductive materials outside its insulating-material scope still need an appropriate method with the same discipline of geometry and conditioning.

For ESD, the actual electrode arrangement and applied voltage can change a nonlinear material response. Surface texture and print roads alter electrode contact. The test voltage, electrification time, reading time, relative humidity, temperature and electrode mass or pressure should be recorded. Charge-decay tests declare the charging method, initial level, endpoint and ground path. System-to-ground testing includes inserts and fasteners in their assembled state.

For EMI, the empty/reference fixture, specimen aperture, thickness, orientation, polarization and instrument dynamic range are recorded. Leakage around the specimen can become the measured limit. Multiple orientations expose print anisotropy. If reflection and absorption components are reported, the conversion from scattering parameters and any assumptions are preserved. A comparison uses the same fixture and frequency grid.

For thermal transport, density and heat capacity are not generic constants when conductivity is computed from diffusivity. Filler loading, crystallinity, porosity and temperature change them. Direction labels follow the heat-flow axis, not simply the face on which a specimen was printed. Contact pressure and interface material are specified for steady-state impedance tests. Coatings used to control optical absorption or emissivity are reported because they can affect thin specimens.

Uncertainty has at least four layers: instrument and calibration; specimen dimensions and contacts; within-build spatial variation; and between-batch/build variation. A small standard deviation from repeated instrument readings cannot represent production variability. Acceptance compares the full uncertainty and population to the specification guard band.

The test method is checked for resolution near the decision boundary. Very high resistance can approach leakage limits; very low resistance can be dominated by leads and contacts; high shielding can approach fixture leakage; high thermal resistance can amplify edge losses. A censored value such as “greater than” or “below detection” is not silently converted into an exact number.

13. Ageing, environmental coupling and occupational control

Functional networks evolve. Thermal cycling expands matrix and filler differently, changing contacts and interfacial stress. Humidity plasticizes polymers, changes ionic conduction and oxidizes metals. Mechanical bending or vibration opens junctions. DC bias can drive electrochemical migration. RF heating can localize at defects. UV or chemical exposure can degrade the matrix. Qualification selects stressors from the intended service rather than applying a generic ageing list.

Resistance should be monitored during cycling when transient opening matters. A post-test reading can miss intermittent failure. Thermal devices should be cycled at representative power and contact pressure, with source temperature and interface condition monitored. Shields should be retested after seam opening, fastener cycling and coating abrasion. ESD fixtures should be tested after cleaning and wear, not only after storage.

Metallic traces and coatings require adhesion, bend or fatigue, corrosion and migration evidence appropriate to voltage, humidity and contaminants. Silver can migrate under an electric field and moisture; copper can oxidize; nickel or other barrier layers can alter contact and environmental behaviour. The route specification includes the complete stack and thickness, not only the outer metal name.

Conducting polymers can depend strongly on water, counterions and dopant state. A dry conductivity does not qualify a wet bioelectronic use, and a wet impedance does not qualify a dry interconnect. Oh et al. [25] and Yuk et al. [26] deliberately evaluated specified states and devices. Industrial transfer must retain that state label and add the application’s sterilization, extractables, shelf life or environmental needs where relevant.

Nano/micron safety is state-dependent. A bound filler in a finished composite can become airborne during compounding, powder handling, sanding, failed-print cleanup or recycling. ISO/TR 13014 links physico-chemical characterization to toxicological assessment [34]. NIOSH provides nanotechnology guidance [37], specific recommendations for occupational exposure to CNTs and carbon nanofibres [38], and health-effect guidance for silver nanomaterials [39]. These sources support hazard recognition and control; they do not provide a single permission threshold for every formulation.

Engineering controls are designed around the task: closed transfer, local exhaust, containment, wet cleanup, filtered vacuum, maintenance procedure and waste handling. Exposure assessment distinguishes background from process emission and identifies the nanoform. Personal protective equipment is a layer, not a substitute for containment. A route whose performance depends on uncontrolled dry nanopowder handling fails the factory gate even if its coupon is excellent.

Thermal and conversion operations add solvent vapour, decomposition products, combustible dust, reactive precursor and hot-surface hazards. Plating adds bath chemistry and waste. Laser conversion adds optical and fume hazards. The route selection compares the entire cell and accepted yield, not material cost per kilogram.

14. Qualification genealogy and change control

A qualified product connects seven records. The **requirement record** defines the function, boundary, comparator and acceptance rule. The **material record** identifies every functional phase, matrix, additive, surface treatment, lot and storage state. The **formulation record** captures mass and volume fractions, sequence, energy, temperature, air removal, stability and hold time. The **build record** captures equipment, nozzle or optics, toolpath, orientation, location, environment and process signals. The **transformation record** captures cure, wash, dry, anneal, sinter, infiltrate, plate or condition history. The **test record** preserves specimen and device methods, raw data, uncertainty and failures. The **disposition record** ties accepted items and deviations to authorized evidence.

Change control is functional rather than clerical. A new filler supplier, nanoform, surface treatment, particle distribution, dispersant, polymer lot, nozzle material, toolpath, layer height, cure dose, anneal profile, plating bath, electrode adhesive or thermal-interface material can change the network. Software and geometry changes can alter orientation and current or heat paths. Each change is screened for which causal links it touches and triggers the corresponding requalification.

Reference coupons should travel with production but cannot substitute for the product. A witness bar can detect formulation drift; it may not detect a shield seam or deep coating failure. Coupon placement should sample build-time and spatial extremes. Device-level tests close interfaces and geometry.

Statistical control uses physically meaningful variables. Filler mass alone can remain constant while dispersion or orientation drifts. Useful signals can include mixing torque, viscosity at selected histories, density, deposited mass per length, resistance between in-process fiducials, cure conversion, coating thickness map, thermal contact impedance or EMI leakage at a sentinel frequency. Limits are linked to accepted product data.

Table 3. Minimum linked evidence for functional qualification

Record	Controlled content	Functional evidence	Change that reopens the record
Requirement	Function, state, path, direction, environment, comparator and guard-banded limit	Approved measurement and device acceptance plan	New device boundary, load, frequency, temperature, humidity or life

Record	Controlled content	Functional evidence	Change that reopens the record
Material/formulation	Supplier lot, nanoform, surface, matrix, additive, mass/volume fraction, mixing energy and hold	Identity, dispersion/network proxies, rheology, stability and hazard controls	Supplier, grade, surface treatment, dispersant, fraction, sequence or storage
Build/transformation	Machine, nozzle/optics, orientation, toolpath, position, cure/dry/anneal/sinter/plate history	Direction-labelled coupons, density, local structure and process signals	Hardware, software, geometry, layer, path, exposure, thermal cycle or bath
Contact/interface	Electrode, insert, adhesive, coating, gasket, thermal interface, pressure and preparation	Intrinsic result plus representative joint/contact resistance or impedance	Contact material, finish, pressure, preparation, thickness or assembly sequence
Test/ageing	Raw data, drawing, method, conditioning, uncertainty, population, stress cycles and failures	Initial and aged coupon, subcomponent and device conformity	Method, fixture, laboratory, conditioning, cleaning or service profile
Disposition	Accepted serials/lots/builds, deviations, repairs and responsible authorization	Traceable pass, reject or conditional engineering decision	Any unapproved deviation or evidence break

15. Applied route selection: an electronics assembly fixture

Consider a reusable fixture that supports an electronic assembly during inspection. It contains a broad base, locating nests and a removable heated calibration module. The fixture must avoid charge accumulation on operator-accessible surfaces, provide a verified path to ground, remain electrically insulating around exposed test pads, remove heat from the calibration module to a metal frame, tolerate routine cleaning and remain dimensionally stable. It is not required to carry load current or provide a full RF enclosure.

The initial, poorly formed request is “print the fixture in a conductive material.” The state-resolved requirement separates three zones. Zone A, the operator-accessible body and nests, requires controlled dissipative behaviour and a durable system-to-ground path. Zone B, guards around exposed test pads, requires electrical insulation and verified spacing. Zone C, beneath the calibration module, requires a short thermal path to the frame while remaining electrically insulating. A replaceable metal ground insert and mechanically protected connection are allowed.

Three candidate architectures are screened. **Route 1** uses one carbon-filled thermoplastic for the entire fixture. It could satisfy Zone A, but it creates risk in Zone B and may provide insufficient through-thickness heat transport in Zone C. High carbon loading can also reduce inter-road fusion and dimensional toughness. The route survives only if local insulating barriers and thermal performance close; the “one material” simplicity is not assumed.

Route 2 uses an insulating structural polymer, a selectively applied or co-printed dissipative carbon region connected to a ground insert, and a metal coating for thermal transfer. It protects Zone B by material allocation and can localize conductivity. It is rejected if the coating cannot access or adhere beneath the module, if the plating chemistry damages tolerances, or if coating-to-frame contact dominates thermal impedance.

Route 3 uses an insulating structural polymer, a dissipative insert or replaceable surface element for Zone A, and a BN-filled electrically insulating heat-spreader insert for Zone C. It separates ESD and thermal functions and keeps the pad guards insulating. It adds assembly interfaces and inventory but allows each zone to use an appropriate test. This route is provisionally preferred when replaceability and inspection outweigh monolithic manufacture.

Table 4. Route screen for the electronics fixture

Decision element	Route 1: carbon-filled monolith	Route 2: insulating print plus dissipative region and metal coating	Route 3: insulating body plus dissipative and BN-filled inserts
Zone A ESD path	Potentially direct, but verify dry-humidity extremes, road continuity and ground insert	Localized path; coating/region continuity and joint must be mapped	Replaceable element can be separately qualified; interface to ground remains critical
Zone B insulation	Inherent conflict; needs added barrier and breakdown/creepage evidence	Preserved in uncoated regions; masking and overspray become controls	Preserved by base polymer and geometric separation
Zone C heat path	Carbon may conduct mainly along roads; electrical conduction near pads is undesirable	Metal can lower surface resistance to heat flow but coating/contact coverage may limit through-thickness transfer	BN-filled insert targets heat transport while retaining insulation; orientation and contact pressure must be qualified
Manufacturability	One feedstock, but narrow filler/process window and abrasive wear	Multiple operations, surface activation and chemical process	Multiple printed parts and controlled assembly; easier material-specific processing
Inspection and repair	Internal network difficult to inspect; whole fixture may be scrapped	Coating thickness/continuity inspectable where accessible; local repair possible	Inserts, ground path and interface can be inspected or replaced separately
Primary no-go	Any exposed region fails insulation, ESD tail exceeds limit, or thermal path misses target	Masking/coverage, adhesion or interface cannot be controlled	Insert interfaces cannot maintain geometry, ground or thermal contact through life

The provisional selection does not authorize production. A designed experiment spans candidate dissipative material lots, print orientations, low and nominal humidity, cleaning cycles and ground-insert assembly. Zone A is measured for surface resistance or resistivity with the selected standard geometry, system-to-ground resistance and use-cycle charge behaviour. Zone B is measured for insulation resistance and the application’s electrical safety boundary. Zone C is measured for direction-resolved thermal transport and, more importantly, source-to-frame thermal impedance at controlled contact pressure.

The build includes coupons parallel and perpendicular to roads and through thickness. The fixture itself carries in-process test points between representative nests and ground. The thermal insert is printed in at least two toolpath orientations to test whether platelet alignment connects source to frame. Thermography uses a controlled emissivity surface and is paired with contact temperature sensors.

Ageing combines the actual cleaning fluid, repeated assembly, thermal duty cycles and mechanical load. Acceptance is based on all three zone functions after ageing. A failure in Zone A does not trigger more BN in Zone C; a thermal failure does not justify lowering electrical insulation. The architecture keeps corrective action causal.

The decision output records delivered state, candidate routes, mandatory transformations, invalidation gates, factory constraints, evidence gaps, surviving architecture and no-go rationale. This is the operational bridge between a literature review and an engineering programme.

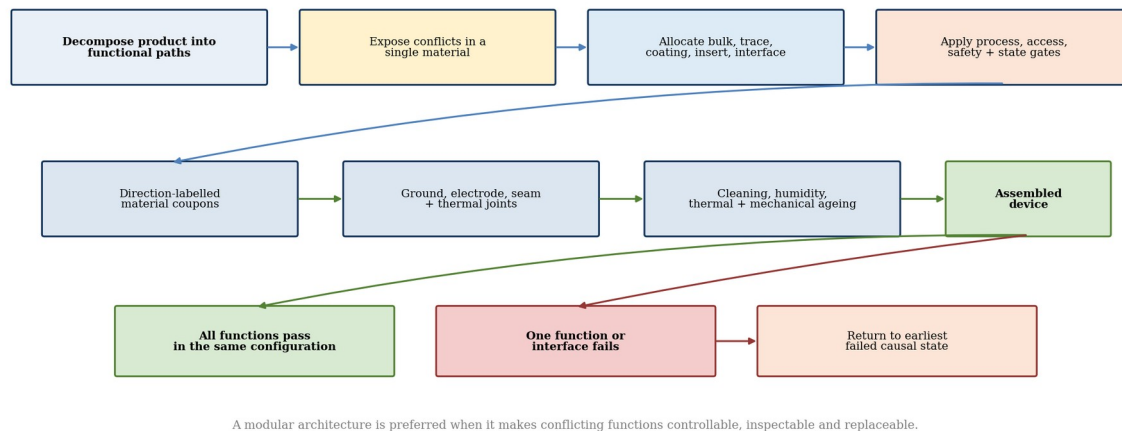


Figure 2. Function-allocation and qualification decision for a multi-zone printed component.

16. Discussion: what additive manufacturing changes

Additive manufacturing does more than shape a pre-existing functional material. It creates transport architecture. Nozzle flow aligns fillers. Droplet drying redistributes them. Layer fusion creates barriers. Optical cure changes separation. Powder coating creates segregated networks. Toolpath decides whether local anisotropy is useful. Post-processing develops or damages contacts. The process file is therefore part of material identity.

This insight changes how “pros and cons” should be written. A carbon-filled filament does not have one advantage and one disadvantage. Its advantage may be an accessible dissipative path in an XY surface at low humidity after a specified anneal and contact preparation. Its disadvantage may be build-direction variability, nozzle wear and weak fusion at the loading required. The comparator may be a plated polymer or replaceable dissipative insert, not neat polymer. Without state, direction and comparator, a pros-and-cons table is advertising rather than engineering.

The literature supports mechanisms and plausible routes. Gnanasekaran et al. [15] support process sensitivity of carbon networks in extrusion. Guan et al. [17], Shi et al. [19] and Xiong et al. [20] support micro/macrostructural control of EMI performance through different AM routes. The BN studies [21–24] support thermally functional, electrically insulating composites and their anisotropy. The PEDOT:PSS studies [25–27] support formulation- and state-dependent conducting polymers. The metal-ink and metallization studies [28–31] support direct and hybrid conductor formation. None provides a universal property table because the measured systems differ.

The most important industrial decision may be to stop asking one filled polymer to do everything. Electrical conduction and insulation are direct conflicts in the same zone. ESD and low-resistance current carrying can require different resistance domains. EMI and heat management can share conductive networks, but seams, frequency and thermal interfaces diverge. Modular material allocation can reduce the amount of functional filler, simplify exposure control and make repair possible.

There is also a scale distinction. A material can pass a centimetre coupon and fail a metre-equivalent current path because resistance and defect probability accumulate. A shield can pass a small aperture and fail at a product seam. A thermal coupon can look favourable while a real contact is warped. Scaling laws and extreme-value behaviour must be considered before a prototype claim becomes a production claim.

Qualification should resist headline optimization. Near electrical percolation, small formulation changes can create large resistance variation; that sensitivity can be useful for sensors and hazardous for stable conductors. Maximum EMI shielding can carry density or reflection penalties. Maximum filler loading can destroy print yield. Maximum in-plane thermal conductivity can leave the required through-plane path unchanged. The optimum is the robust accepted device yield under factory and service constraints.

Digital manufacturing adds an opportunity: orientation and function can be encoded in the toolpath. Compton and Lewis showed flow-created reinforcement architecture in printed cellular composites [32], while Kokkinis and co-workers demonstrated field-assisted control of platelet orientation [33]. Those mechanisms are relevant to functional transport because the same orientation that directs reinforcement can redirect electrical or thermal pathways. The opportunity is credible only when the orientation field is measurable, linked to process parameters and preserved through slicing and software revisions. A hidden change in infill order can be a material change. Machine-learning or simulation tools can help design paths, but their predictions require local microstructure and boundary-condition validation.

Evidence should be layered. Mechanistic evidence explains why a variable might matter. Coupon evidence shows that a controlled process produces a property distribution. Subcomponent evidence closes contacts, seams and interfaces. Device evidence closes the real boundary conditions. Production evidence shows stable yield and controlled change. Skipping a layer leaves an unknown, not a transferable assumption.

17. Conclusions and research priorities

1. Electrical conduction, electrostatic control, EMI shielding and thermal transport are distinct functions and must not share one generic “conductivity” claim.
2. The qualifying object is the complete material–process–geometry–interface–test system in the state and direction of intended use.
3. A filler name or intrinsic filler property cannot establish printed-part function. Volume fraction, morphology, dispersion, orientation, interfaces, porosity, cure and contacts control the network.
4. Electrical percolation is not a universal loading. It is a formulation- and process-created transition whose position and variability can change with mixing, printing, ageing and measurement geometry.
5. Better dispersion is not synonymous with better conduction. The target is a repeatable, printable and durable connected population, not the smallest observable agglomerate.
6. ESD qualification requires material tests, grounding architecture, charge behaviour and programme-level verification under realistic humidity, cleaning and wear.
7. EMI shielding results are bounded by frequency, field regime, thickness, density, polarization and fixture. Planar coupon performance does not qualify an enclosure with seams, apertures and cables.
8. Thermal conductivity, diffusivity, impedance and contact resistance answer different questions. Direction, density, heat capacity, pressure and interfaces must accompany the result.
9. Additive manufacturing creates anisotropy through filament production, nozzle flow, droplets, recoating, cure and layers. At least three orthogonal directions should be considered when the product path is not planar.
10. Contacts and interfaces deserve their own resistance or impedance budget. Intrinsic-material tests and representative-joint tests are both required.
11. Retained composites, conducting-polymer inks, printed metals, metallized polymers, infiltrated structures and ceramic-filled heat spreaders are alternative architectures, not points on one filler ranking.
12. Multi-zone designs often outperform a monolithic functional composite because conduction, insulation, ESD and heat paths can be allocated and inspected separately.
13. Safety and factory controls belong to route selection. A high-performing coupon does not compensate for uncontrolled nanopowder, solvent, plating or conversion exposure.
14. Change control must include material nanoform, surface treatment, formulation, nozzle, toolpath, software, cure, conversion, contacts and cleaning whenever they touch the causal network.
15. Literature values should be used to identify mechanisms, variables and test architectures. They should not be transferred as acceptance limits to another feedstock or device.

Research should now focus on interlaboratory methods for direction-resolved printed transport; non-destructive mapping of local electrical and thermal networks; reference geometries that connect coupon anisotropy to device paths; ageing models near percolation; standardized reporting of EMI thickness, density and architecture; measurement of deep-coating continuity in complex prints; and digital thread methods that preserve material state, orientation and interface genealogy from formulation through service.

The practical rule is simple but demanding: define the function and path first, create the network deliberately, measure it in the relevant state and direction, close every interface in the assembled device, and accept only the configuration whose full evidence remains coherent after ageing and change review.

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