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Systematic Review

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Defect Formation, Detection, and Quality Assurance in Additive Manufacturing: A Systematic Review

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Abstract: Additive manufacturing (AM) enables the production of geometrically complex components but introduces process-dependent defects that may compromise dimensional accuracy, surface integrity and mechanical reliability. This systematic review examines defect formation, defect-sensitive quality phenomena, detection and quality assurance across the principal AM process categories, distinguishing discrete manufacturing discontinuities from geometrical deviations, surface-quality attributes and process-dependent material responses. Literature published between 2010 and 2025 was retrieved through CrossRef and screened using a Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA)-informed procedure, resulting in 134 publications included in the final analytical corpus. The synthesis shows that defect formation is governed by interacting material, process and thermal-history variables and that apparently similar defect manifestations can arise from substantially different mechanisms across AM processes. Inspection capability is likewise process- and defect-dependent: X-ray computed tomography (XCT), including micro-computed tomography (μCT), is particularly suited to internal volumetric discontinuities, whereas optical and three-dimensional scanning primarily address external geometry and surface conformity. The principal contribution of the review is an integrated process–material response–quality manifestation–performance–inspection–qualification framework that connects process-dependent defect and quality formation with engineering consequences, inspection capability, quality-assurance decision-making and industrial qualification.

Keywords: additive manufacturing; manufacturing defects; quality assurance; defect detection; surface integrity; anisotropy

1. Introduction

Additive manufacturing (AM) enables the fabrication of geometrically complex, customised and functionally integrated components through layer-wise material deposition or consolidation. Although this capability has expanded the design and manufacturing space available to high-value sectors, the same layer-based process architecture also introduces defect-sensitive mechanisms that are not typically encountered in conventional

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subtractive manufacturing. AM quality degradation may manifest through several conceptually distinct classes of process-induced phenomena. Discrete manufacturing discontinuities, such as porosity, lack of fusion, cracking and delamination, coexist with geometrical deviations, including distortion and layer misalignment; surface-quality attributes, including Surface Roughness (SR) [1]; and material-state or directional responses, including residual stress, microstructural heterogeneity and anisotropic behaviour [2]. Layer slippage [3], where present, is treated principally as a deposition-induced geometrical misalignment rather than as a defect class equivalent to cracking or porosity. Although these phenomena may share common process origins, their physical meaning and engineering significance are distinct.

The formation and engineering significance of these defects and defect-sensitive quality phenomena are strongly influenced by material behaviour, including thermal expansion, viscosity, flowability, solidification response and interlayer bonding characteristics [4]. Process-related variables, including energy input, scan strategy, extrusion temperature, layer height, nozzle diameter, hatch spacing and build orientation, further determine whether defects remain localised, propagate between layers or compromise the dimensional and mechanical reliability of the final component.

Consequently, the industrial adoption of AM depends not only on design freedom or production flexibility, but also on the ability to understand, detect and control defects that compromise dimensional accuracy, surface integrity, mechanical performance and long-term reliability. Advanced inspection and analytical approaches, including computed tomography, three-dimensional scanning, Non-Destructive Testing (NDT) and machine-learning-assisted defect classification, are therefore increasingly important for defect localisation, quality assessment and predictive process control [3,5].

Although defect formation and quality assurance in AM have been addressed by several previous reviews, the available knowledge remains divided among distinct analytical perspectives. Earlier contributions have examined, for example, general quality control across AM technologies, defect and property classification, anisotropy and heterogeneity, surface metrology, NDT, process-specific defect formation, or individual inspection technologies. These studies have provided important foundations for understanding AM quality; however, they generally emphasise either a particular process family, material class, defect category, quality attribute or inspection approach. Consequently, the relationship between the physical origin of a defect, its resulting morphology, its influence on component performance and its practical detectability remains insufficiently integrated at a cross-process level.

The research gap addressed in the present review therefore concerns the need for a common analytical structure capable of connecting defect formation, component performance, inspection and qualification rather than treating these dimensions as largely independent topics. The review consequently adopts an integrated causal and diagnostic framework following the sequence AM process → process/feedstock parameters → material and microstructural response → defect or quality manifestation → performance and reliability → inspection/monitoring evidence → quality-assurance decision → mitigation or process feedback → industrial qualification. This structure recognises that manufacturing parameters first modify the local thermal, rheological, consolidation or bonding conditions, which govern microstructural development and the formation of discontinuities or other quality deviations. The resulting condition subsequently affects component performance and determines the information required from inspection, while inspection evidence supports process correction, component disposition and application-specific qualification.

The scope of the review is cross-process and cross-material but is deliberately not intended as an exhaustive review of every AM material–process combination. The seven principal AM process categories defined by ISO/ASTM are considered as the primary organisational level because process physics governs the mechanisms through which defects are generated and detected. Metallic alloys, polymers, ceramics and composite systems are therefore included as representative material classes where they provide evidence of process-specific or transferable relationships between material response, defect formation, component performance and inspection capability. Architected or lattice structures are considered only where their geometry or material–process interaction provides relevant evidence concerning defect formation, detectability or defect-sensitive performance. Accordingly, the review is neither restricted to metal AM nor centred on Ni-based superalloys; individual materials such as Ti alloys, stainless steels, aluminium alloys or Ni-based superalloys are used as process-specific examples rather than as independent review domains.

The defect scope is similarly selective rather than exhaustive. Attention is given to recurrent process-induced discontinuities and quality attributes that enable cross-process comparison, including porosity and voids, lack of fusion, cracking, delamination or weak bonding, dimensional deviation, SR, anisotropic behaviour and layer slippage. These phenomena are examined according to their generation mechanisms, resulting morphology or material response, consequences for component performance and suitability for detection or monitoring. The

objective is therefore to establish transferable process–material–defect–performance–detectability relationships, rather than to catalogue every reported AM defect or material system.

To establish the position of the present contribution within the existing literature, Table 1 compares representative previous reviews addressing AM defects, quality control, surface condition and non-destructive inspection. The comparison demonstrates that the present study is distinguished primarily by its cross-process integration of defect-generation mechanisms, performance consequences and detection capability, rather than by the isolated treatment of any individual defect or inspection technology.

Table 1. Positioning of the present review relative to representative previous reviews on AM defects, quality control and inspection.

Ref	Principal Scope	Principal Limitation Relative to the Present Review
[6]	Quality control in AM	Broad quality-control perspective; does not systematically connect individual defect-generation mechanisms with performance consequences and defect-specific detectability.
[7]	Influence of defects on mechanical properties in metal AM	Strong defect–performance treatment, but centred on metal AM and XCT rather than cross-process inspection and quality assurance
[8]	Non-destructive quality control in AM	Inspection-centred review; causal links between process conditions, defect formation and resulting performance are not its principal analytical structure
[9]	Classification of defects and properties generated by AM processes	Provides a valuable cross-process defect classification, but does not systematically integrate defect-specific detectability and inspection capability with performance consequences
[10]	Defects and anomalies in metal powder bed fusion (PBF)	Detailed process–defect treatment but restricted to metallic PBF and therefore not intended as a cross-process quality-assurance framework
[11]	AM and NDT	Comprehensive inspection perspective, but defect formation, performance consequence and detectability are not integrated within a single cross-process causal framework.
[12]	Defects in vat-photopolymerised ceramics	Restricted to one AM process family and one material class
[13]	Multi-scale defects in fibre-reinforced material extrusion (MEX)	Detailed defect-detection treatment but restricted to material extrusion and fibre-reinforced thermoplastic composites
[14]	Surface analysis in PBF	Focused specifically on surface condition and PBF; does not encompass internal defect classes or cross-process defect–performance–detectability relationships
Present review	Defect formation, detection and quality assurance	Integrates process-dependent defect generation, defect manifestation, performance consequence and detectability within a common quality-assurance framework

The present review focuses on peer-reviewed literature addressing defect formation, manifestation, performance consequences, detection and quality assurance across the principal AM process categories. The scope encompasses MEX, vat photopolymerisation (VPP), material jetting (MJT), sheet lamination (SHL), PBF, directed energy deposition (DED) and binder jetting (BJT), together with the principal material, processing and inspection variables that determine defect occurrence and detectability. The review is intentionally cross-process and cross-material: individual alloys, polymers, ceramics and composites are considered where they provide evidence of transferable or process-specific defect mechanisms rather than as independent material-centred review domains. Table 2 summarises the five principal Research Questions (RQ).

Table 2. Overarching research questions guiding the systematic review.

ID	Research Question
RQ1	What are the principal technical challenges affecting the identification, classification and reliable detection of defects in AMed parts across different AM processes?
RQ2	How do inspection, monitoring and analytical strategies determine the effectiveness of defect detection and quality assessment in AMed parts?
RQ3	How do process parameters, inspection configurations and technology selection influence the reliability, repeatability and diagnostic capability of defect detection in AM?
RQ4	What recent developments in monitoring systems, analytical methodologies and digital inspection tools contribute to improved defect detection and quality assurance in AM?
RQ5	What are the emerging research trends, unresolved methodological limitations and future opportunities in the study and detection of defects in AMed parts?

These questions are addressed through the same causal and diagnostic sequence: AM process → process/feedstock parameters → material and microstructural response → defect or quality manifestation → performance and reliability → inspection/monitoring evidence → quality-assurance decision → mitigation/process feedback → industrial qualification. This sequence provides the organisational framework for the subsequent literature synthesis and enables evidence from different AM processes to be compared according to common causal relationships rather than as isolated study outcomes.

1.1. Contextualisation of AM

The defect landscape in AM is intrinsically process- and material-dependent because the principal process categories rely on fundamentally different mechanisms of material deposition, consolidation, bonding and solidification [15–17]. In thermally driven metallic processes such as PBF and DED, steep thermal gradients, melt-pool instability, rapid solidification and residual-stress accumulation promote phenomena such as porosity, lack of fusion, cracking, distortion and microstructural anisotropy [18]. By contrast, MEX, SHL, MJT, VPP and BJT involve different defect-generation mechanisms associated with interlayer bonding, material-flow stability, curing behaviour, sheet alignment, binder distribution, densification and shrinkage [17,19,20].

These differences prevent AM quality from being interpreted through a single process-independent defect taxonomy [20,21]. Identical defect descriptors may arise from distinct physical mechanisms and may have different consequences for dimensional conformity, surface integrity and mechanical performance. Porosity, for example, may result from insufficient fusion or keyholing in PBF, incomplete densification in BJT, unstable melt-pool behaviour in DED or inter-bead void formation in MEX. Likewise, the applicability and sensitivity of inspection techniques depend on the defect morphology, material system, component geometry and manufacturing route [20,22].

Accordingly, the present review considers the principal AM process categories as the first level of an integrated analytical framework linking process conditions → defect-generation mechanisms → defect manifestation → performance consequence → detectability and quality-assurance response [23]. Material-specific examples are used where they provide evidence of these relationships, but the scope is intentionally cross-process rather than centred on a single alloy, polymer or application sector.

1.2. AM Classification

The process classification adopted throughout this review follows ISO/ASTM 52900:2021, which defines seven principal AM process categories: MEX, VPP, MJT, SHL, PBF, DED and BJT [24]. These categories are retained as the primary process-level structure of the review because differences in material delivery, consolidation, bonding and thermal history directly influence defect-generation mechanisms, resulting defect morphologies and applicable inspection strategies. Figure 1 summarises the adopted classification.

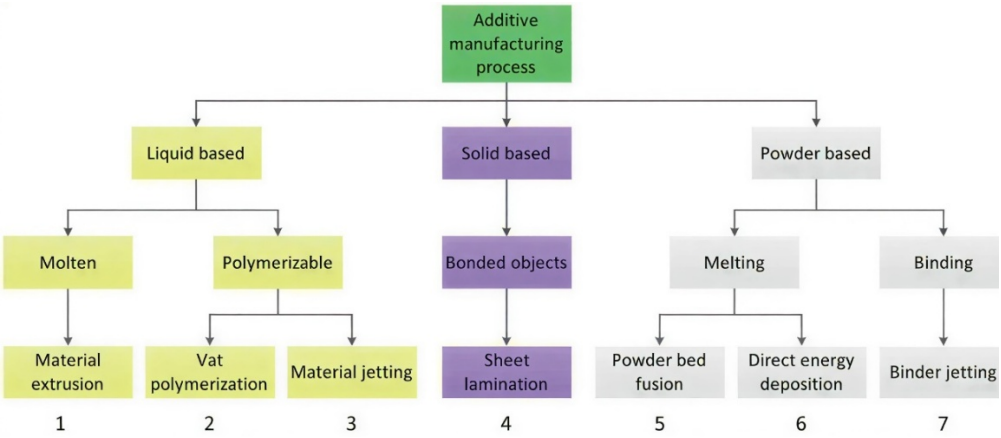


Figure 1. Classification of AM processes [4].

1.3. Importance of Defect Detection

Defect detection in AM should be considered within the broader relationship between process variability, defect formation, component performance and qualification rather than as an isolated inspection activity. Process-induced discontinuities may differ substantially in morphology, spatial distribution and engineering significance depending on the manufacturing route, material system, component geometry and subsequent loading condition [7,9,25,26].

Consequently, the value of an inspection technique depends not simply on whether a discontinuity can be detected, but on whether the method provides sufficient sensitivity, spatial resolution and morphological information to support a technically meaningful quality-assurance decision [8].

This requirement creates a direct connection between defect-generation physics and inspection strategy. Volumetric discontinuities such as internal porosity and lack of fusion favour techniques capable of resolving internal morphology, whereas dimensional deviations and surface-related features require surface-oriented metrology. Interfacial defects, weak bonding and process-induced heterogeneity may require complementary inspection or monitoring approaches [9,19]. The relevant engineering problem is therefore not to identify a universally superior inspection technology, but to establish a process- and defect-specific correspondence between the expected defect population, its performance consequence and the measurement capability required for reliable qualification.

1.4. Classification of Defects

A rigorous interpretation of AM quality requires a distinction between manufacturing defects, geometrical deviations, surface conditions, material or microstructural states and the resulting performance response [26,27]. Although these phenomena may originate from common process conditions and may interact during manufacture or service, they are not conceptually equivalent. In the present review, the term manufacturing defect is reserved principally for unintended localised or distributed discontinuities that represent loss of material or interfacial continuity, such as pores, lack-of-fusion regions, cracks, delamination and inclusions [26,28].

By contrast, geometrical and dimensional deviations describe departures from the nominal component geometry, including distortion, warpage, shrinkage and layer misalignment [26,29]. Surface-quality attributes, including SR and waviness, describe the resulting surface condition and become non-conforming only when they compromise a specified dimensional, functional or performance requirement [18]. Material-state and microstructural characteristics, including residual stress, crystallographic texture, grain morphology, phase distribution and microstructural heterogeneity, describe the internal material condition produced by the manufacturing route and are not inherently defects. Likewise, anisotropy is treated as a directional material, geometrical or functional response whose acceptability depends on its origin, magnitude and application context rather than as an intrinsic manufacturing defect.

Finally, changes in strength, ductility, stiffness, fatigue life, fracture resistance, thermal response or corrosion behaviour are treated as performance consequences rather than defect classes themselves [26,30]. The analytical distinction adopted in this review is therefore based on the causal sequence: process condition → material response → defect or quality manifestation → performance consequence → detectability and quality-assurance decision. Within this sequence, non-destructive inspection and data-driven classification methods provide complementary means of identifying and differentiating defect manifestations once the physical category under consideration has been established [9,27].

The categories in Table 3 may be causally connected. For example, non-uniform thermal history may generate residual stress as a material-state variable, which may subsequently produce distortion as a geometrical deviation. Similarly, insufficient consolidation may generate lack-of-fusion discontinuities that act as stress concentrators and reduce fatigue performance. The taxonomy therefore separates the physical condition observed from its origin and subsequent engineering consequence.

Table 3. Taxonomy of manufacturing defects and defect-sensitive quality phenomena adopted in the present review.

Analytical Category	Definition within This Review	Representative Examples	Interpretation
Discrete manufacturing discontinuities	Unintended local or distributed loss of material, continuity or interfacial integrity	Porosity, voids, lack of fusion, cracks, delamination, inclusions	Treated as manufacturing defects
Geometrical and dimensional deviations	Departure of the manufactured component from the intended geometry or dimensional condition	Distortion, warpage, shrinkage, layer slippage/misalignment, dimensional error	Quality deviation; becomes non-conforming relative to tolerance/function
Surface-quality attributes	Measurable characteristics of the external surface produced by layer-wise manufacture and post-processing	SR, waviness, stair-stepping, surface irregularity	Surface condition; not intrinsically a discrete defect
Material-state and microstructural characteristics	Process-dependent internal material condition	Residual stress, texture, grain morphology, phase distribution, heterogeneity	May promote defects or affect performance but is not intrinsically a defect.
Directional material or structural response	Dependence of a measured property or behaviour on direction	Mechanical, thermal, geometrical or shrinkage anisotropy	May be inherent, undesirable or deliberately exploited depending on application
Performance consequences	Resulting engineering response of the manufactured component	Strength, ductility, stiffness, fatigue life, fracture resistance, corrosion response	Consequence of preceding conditions rather than a defect class

Building upon the research gap and research questions defined above, Table 4 operationalises the central analytical framework of the review. The framework does not treat process category, material system, defect type and inspection technology as independent descriptors. Instead, it follows the causal and diagnostic sequence: process → material response → defect-generation mechanism → defect morphology → performance consequence → detection method → mitigation or quality-assurance response. This structure enables apparently similar defect manifestations to be interpreted according to their physical origin and material context, while simultaneously linking them to their engineering significance and practical detectability. It also provides a common basis for comparing evidence across AM process families and for distinguishing process-specific mechanisms from relationships that recur across different manufacturing routes.

Table 4 operationalises the process-to-inspection portion of this framework, whereas Table 5 extends the analysis to fitness-for-purpose quality-assurance decisions and Section 6 considers the subsequent transition towards process feedback and industrial qualification.

The cross-process comparison demonstrates that defect classification becomes substantially more informative when material response and defect-generation mechanism are considered together with morphology, engineering consequence and detectability. The same nominal defect category cannot necessarily be transferred directly between AM routes because its physical origin, resulting morphology, performance consequence and inspection response may differ markedly with process physics and material behaviour. Porosity, for example, may originate from lack of fusion or keyholing in PBF, incomplete densification in BJT, inter-bead void formation in MEX or unstable melt-pool behaviour in DED. Similarly, surface irregularities may result from stair-stepping, partially fused powder, droplet instability, sheet-processing effects or support interaction. The framework therefore extends conventional defect taxonomy into a relational quality-assurance structure that is used throughout the subsequent synthesis to interpret cross-study differences, inspection requirements and mitigation strategies.

Direct ordinal ranking of defect prevalence or inspection suitability across AM processes is not considered appropriate because the reviewed studies differ substantially in material system, processing conditions, specimen geometry, defect definition, inspection configuration and reporting practice. Consequently, the available evidence does not support universal “high”, “medium” or “low” classifications without introducing arbitrary thresholds. Cross-process relationships are therefore interpreted mechanistically through the integrated framework presented in Table 4 and are subsequently examined through cross-study synthesis in Section 4.1. This approach preserves the process dependence of defect formation and inspection capability rather than implying quantitative comparability where the underlying studies do not provide a common measurement basis.

Defect criticality and industrial acceptance cannot be assigned solely from defect type or from a universal severity label. Their engineering significance depends on defect size, morphology, orientation, location, recurrence, component geometry, loading condition, material behaviour, service environment and the functional requirements of the intended application. Consequently, acceptance or rejection should be established through documented fitness-for-purpose criteria, applicable dimensional or material specifications, process-qualification requirements and, where relevant, sector- or product-specific standards. Table 5 therefore presents an application-dependent quality-assurance framework rather than a universal defect-severity ranking.

Accordingly, the terms acceptance, rework and rejection are used in this review only in an application-dependent sense. A defect that is tolerable in a non-critical component may be unacceptable in a fatigue-critical, pressure-containing or safety-relevant application. The present review therefore does not propose universal defect-size or severity limits; such limits must be established against the requirements governing the specific material–process–component–service combination.

Within the taxonomy adopted above, anisotropy, SR and layer slippage are deliberately not treated as equivalent manufacturing defects. Anisotropy is considered a directional material or structural response; SR is considered a surface-quality attribute; and layer slippage is treated primarily as a deposition-induced geometrical deviation within material-extrusion processes. Their inclusion reflects their usefulness for examining three different consequences of layer-wise manufacturing—direction-dependent material response, process-generated surface condition and geometrical/deposition instability—rather than an assumption that they represent the same class of defect.

Dedicated discussion is retained for anisotropic behaviour and SR because both recur across multiple AM routes and provide important links between process history, material response and functional performance. Layer slippage, by contrast, is considered within the material-extrusion synthesis as a process-specific example of layer misregistration and is not presented as a universal AM defect category. Discrete discontinuities such as porosity, lack of fusion, cracking and delamination remain separately represented throughout the cross-process framework and subsequent synthesis.

Table 4. Integrated process–material–quality–performance–detectability framework adopted for the critical synthesis of AM quality assurance.

AM Process	Representative Material Systems in the Reviewed Evidence	Dominant Defect-Generation Mechanisms	Representative Defect or Quality Manifestation	Main Performance Consequences	Suitable Detection Approaches
MEX	Thermoplastic polymers, including PLA; fibre-reinforced thermoplastic composites.	Insufficient melt flow, poor interlayer bonding, inadequate extrusion temperature, raster-path effects, cooling shrinkage and build-orientation dependence	Voids, inter-bead gaps, layer slippage, delamination, warpage, dimensional deviation and SR	Reduced tensile and compressive strength, anisotropic behaviour, poor fatigue resistance, leakage paths and dimensional inaccuracy	Visual inspection, optical scanning, surface profilometry, thermography, mechanical testing and CT for internal voids
VPP	Photopolymer resins, polymer/polymer-composite systems and ceramic-containing photopolymer systems	Incomplete curing, over-curing, light scattering, resin shrinkage, support interaction and post-curing variability	Dimensional distortion, uncured regions, surface waviness, trapped resin, cracks and weak interlayer adhesion	Loss of dimensional fidelity, brittle behaviour, reduced accuracy, poor surface integrity and compromised functional reliability	Optical inspection, 3D scanning, microscopy, dimensional metrology and CT for internal features
MJT	Photopolymer and photoacrylic resins; multi-material PolyJet systems	Droplet spreading, coalescence instability, curing heterogeneity, material cross-contamination and support-removal effects	SR, stair-stepping, dimensional deviation, weak interfaces and local material heterogeneity	Reduced surface quality, poor dimensional accuracy, local mechanical inconsistency and impaired aesthetic or functional performance	Surface profilometry, optical microscopy, 3D scanning, image analysis and mechanical testing
SHL	Polymer-, ceramic- and paper-based laminates; metallic sheets; composite and heterogeneous laminates	Incomplete bonding, poor adhesive distribution, sheet misalignment, cutting inaccuracies and trapped defects between layers	Delamination, weak interfaces, voids, dimensional mismatch, surface defects and layer separation	Reduced interlaminar strength, poor structural integrity, anisotropy and premature failure under bending or fatigue loading	Ultrasonic testing, thermography, visual inspection, optical scanning, peel testing and interlaminar testing
PBF	Metallic alloys including 316L stainless steel, INCONEL® 718, AlSi10Mg and Ti-6Al-4V	Insufficient or excessive energy input, unstable melt-pool behaviour, poor powder spreading, spatter, keyholing, lack of fusion and residual-stress accumulation	Porosity, lack of fusion, keyhole pores, balling, cracks, distortion, rough surfaces and inclusions	Reduced density, fatigue-life reduction, crack initiation, anisotropy, poor surface integrity and dimensional distortion	X-ray CT, metallography, SEM, optical tomography, *in-situ* monitoring, surface profilometry and ultrasonic testing
DED	Metallic alloy systems, including Ti-6Al-4V	Thermal gradients, unstable melt pool, feedstock fluctuation, dilution effects, remelting, oxidation and residual-stress development	Cracking, porosity, lack of fusion, dilution defects, distortion, oxidation and microstructural heterogeneity	Reduced structural reliability, anisotropic mechanical response, poor fatigue behaviour, residual-stress-driven distortion and repair-quality variability	CT, ultrasonic inspection, thermography, melt-pool monitoring, metallography and dimensional scanning
BJT	Metallic systems, including steels, together with ceramic systems such as SiC	Binder-saturation variability, powder-packing heterogeneity, green-part fragility, depowdering damage, sintering shrinkage and incomplete densification	Porosity, dimensional shrinkage, anisotropic distortion, weak bonding, cracks and SR	Reduced density, dimensional inaccuracy, low mechanical strength, anisotropic shrinkage and poor repeatability	CT, dimensional metrology, optical scanning, density measurement, microscopy and mechanical testing

Note: The material systems listed are representative of the evidence synthesised for each AM process category and should not be interpreted as an exhaustive inventory of materials processable by the corresponding technology.

Table 5. Application-dependent industrial criticality and fitness-for-purpose framework for AM defect and quality conditions.

Defect or Quality Condition	Potential Engineering Consequence	Variables Governing Criticality	Appropriate Quality Assessement (QA) Response	Basis for Acceptance
SR or dimensional deviation	Reduced dimensional fidelity, fatigue resistance, tribological performance or functional fit	Magnitude, location, surface function, loading, tolerance and post-processing condition	Surface metrology, optical scanning, profilometry and dimensional verification	Drawing tolerances, functional requirements and application-specific specifications
Porosity, voids or lack-of-fusion regions	Reduced density, local stress concentration, fatigue degradation or loss of leak-tightness	Size, morphology, connectivity, orientation, location and loading condition	Volumetric inspection, defect characterisation and correlation with performance where required	Component function, loading condition, qualification requirements and applicable defect-acceptance criteria
Cracks, delamination or weak interfaces	Crack propagation, loss of structural integrity or reduced interlaminar performance	Length, orientation, location, stressed volume, interface condition and service loading	Targeted NDT, root-cause assessment and engineering disposition	Fitness-for-purpose assessment and applicable structural-integrity or qualification requirements
Residual-stress-related distortion	Dimensional non-conformity, assembly problems or increased cracking susceptibility	Stress magnitude and distribution, component geometry, restraint condition and post-processing route	Dimensional metrology, process review and stress-relief assessment where appropriate	Dimensional tolerance, process qualification and functional requirements
Microstructural or directional heterogeneity	Direction-dependent mechanical response or local variation in performance	Build orientation, thermal history, texture, material system and loading direction	Microstructural/mechanical characterisation and orientation-sensitive qualification	Required mechanical properties and service-specific performance criteria

1.5. Anisotropic Behaviour and Direction-Dependent Material Response

Anisotropy in AM describes direction-dependent variation in material, geometrical, thermal or functional response resulting from the directional nature of layer deposition, heat flow, solidification, interlayer bonding and post-processing. It is therefore not classified in the present review as an intrinsic manufacturing defect. Depending on the material system, process route and design objective, anisotropy may constitute an unavoidable process characteristic, an undesirable quality condition or, in some cases, a deliberately exploited structural feature.

Its engineering relevance consequently depends on the relationship between build orientation, deposition or scan strategy, microstructural evolution, defect population and loading direction. The following synthesis therefore examines anisotropy as a process-dependent material or structural response, with emphasis on its physical origin, consequences for component performance, methods of characterisation and reported strategies for its reduction or controlled exploitation.

Dixit et al. [31] highlighted the difficulty of disentangling the coupled effects of scan rotation angle and build orientation on anisotropy, porosity evolution, texture development and dislocation strengthening in laser powder bed fusion (LPBF) 316L stainless steel. They demonstrated that 67° scan rotation delivered the highest strength and ductility and identified dislocation density—rather than texture alone—as the dominant driver of mechanical anisotropy. Kok et al. [32] tackled the difficulty of consolidating the dispersed literature on anisotropy and heterogeneity in metal AM, particularly the interplay between process conditions, microstructure and mechanical response. Their review identified microstructural features and manufacturing deficiencies as the principal origins of anisotropy and heterogeneity, while outlining predictive modelling and mitigation strategies. Dixit et al. [33] tackled the difficulty of quantitatively capturing mechanical anisotropy in LPBF 316L stainless steel by linking build orientation and scan rotation to microstructure-sensitive constitutive behaviour. An experimentally informed crystal plasticity finite element method (CPFEM) framework was developed and closely reproduced anisotropic tensile behaviour, demonstrating the dominant role of dislocation density alongside grain morphology and texture.

1.5.1. Origin and Engineering Significance

In AM, anisotropy refers to direction-dependent variations in material behaviour, geometry or functional performance within a fabricated component [34]. These variations arise from the layer-wise nature of the process and from the directional character of heat flow, solidification, material deposition, interlayer bonding and post-processing [35]. Depending on the material system and AM route, anisotropy may affect tensile strength, ductility, stiffness, fatigue response, thermal conductivity, dimensional stability and fracture behaviour. Studies on hybrid AM, stochastic lattices, extrusion tooling and binder-jetted components show that anisotropy is governed by the combined effects of build orientation, deposition path, scan strategy, cooling rate, texture development, residual stress, porosity distribution and sintering-related shrinkage [36,37].

The work of Malej et al. [34] on Hybrid AM (HAM) using Ti6-Al4-V highlights the importance of understanding anisotropies for assessing the performance of hybrid processes. The study by Hossain et al. [35] explores the stochastic structures in laser PBF (LPBF) and emphasises the need to overcome manufacturing limitations that lead to anisotropic stiffness. Khalifa et al. [36] study on extrusion die design, and Zago et al. [37] research on BJT further contribute to the understanding of anisotropies by addressing their impact on mechanical properties.

1.5.2. Cross-Study Evidence on Anisotropic Response

Table 6 synthesises representative studies examining the origin, characterisation and control of anisotropic behaviour in AM. The evidence shows that directional response arises from interacting effects of build orientation, deposition or scan strategy, thermal history, texture, grain morphology, porosity, interlayer bonding and post-processing. Importantly, the reviewed studies do not support interpretation of anisotropy as universally detrimental: some investigations seek to minimise directional variation, whereas others deliberately exploit anisotropic response through material, process or structural design. The engineering significance of anisotropy must therefore be evaluated against the intended loading condition and functional requirements of the component.

Table 6. Representative studies on anisotropy in additively manufactured materials and components.

Ref	Material/AM Process	Anisotropic Response—Origin and Governing Variables	Characterisation and Performance Evidence	Control Strategy/ Remaining Limitation
[31]	316L/LPBF	Mechanical anisotropy; scan rotation, build orientation, dislocation density and texture	Mechanical and microstructural characterisation; 67° scan rotation produced the highest reported strength and ductility; dislocation density identified as the dominant contributor	Control: scan-strategy and orientation optimisation. Limitation: coupled texture/ dislocation/orientation effects
[33]	316L/LPBF	Mechanical anisotropy; build orientation, scan rotation and microstructure	Experimentally informed CPFEM reproduced direction-dependent tensile behaviour	Control: process-informed constitutive modelling. Limitation: model transferability requires validation beyond the investigated conditions
[34]	Ti-6Al-4V/hybrid PBF–DED	Microstructural and mechanical anisotropy; heat flow, build orientation, interface integrity and microstructural transition	Microstructural and mechanical assessment; direction-dependent strength and ductility	Control: thermal-history and interface control. Limitation: hybrid-architecture-specific response
[35]	SS316L and Ti-6Al-4V/AM stochastic structures	Structural stiffness anisotropy; strut orientation, morphology and build direction	Multi-directional testing; modified architectures reduced stiffness variation across ten loading orientations	Control: architecture modification. Limitation: geometry-specific behaviour
[37]	BJT	Anisotropic sintering shrinkage; build direction and feature inclination	Dimensional measurement and analytical modelling; linked shrinkage to diameter, cylindricity and axis deviations	Control: shrinkage compensation. Limitation: geometry- and process-dependent
[38]	Porous implant structures/AM	Elastic anisotropy; pore architecture and structural geometry	Geometry–anisotropy mapping; directional stiffness could be tailored towards bone-like response	Control: architecture tailoring. Limitation: application- and geometry-specific
[39]	AM structural components	Printing-induced strength anisotropy; topology and infill orientation	Numerical optimisation; deliberate anisotropy improved stiffness and strength-to-mass performance	Control: joint topology/ infill optimisation. Limitation: design- and process-dependent
[40]	Stainless steel/DED	Microstructural anisotropy; directional heat flow, columnar grains and cyclic reheating	Mechanical/microstructural assessment; P70 condition produced the weakest directional dependence and favourable strength–ductility balance	Control: cyclic phase-transformation strategy. Limitation: material-specific
[41]	Ti-6Al-4V/LPBF	Machinability and surface-response anisotropy; build orientation and microstructure	Post-milling surface/chip assessment; horizontal specimens produced lower burr heights and more favourable chip morphology	Control: orientation-sensitive machining. Limitation: concerns post-processing response
[42]	AlSi10Mg/SLM	Plastic anisotropy and local strain heterogeneity; porosity and microstructure	CT–DIC–ANN linked pore descriptors with strain localisation, anisotropy evolution and crack initiation	Control: defect-aware predictive modelling. Limitation: broader model transferability requires validation
[43]	BCC/Octet lattice structures/AM	Structural anisotropy; topology and shape parameters	Numerical and experimental assessment; anisotropy could be tuned while improving mechanical performance	Control: geometry optimisation. Limitation: lattice-specific response

Table 6. *Cont.*

Ref	Material/AM Process	Anisotropic Response—Origin and Governing Variables	Characterisation and Performance Evidence	Control Strategy/ Remaining Limitation
[31]	316L/LPBF	Mechanical anisotropy; scan rotation, build orientation, dislocation density and texture	Mechanical and microstructural characterisation; 67° scan rotation produced the highest reported strength and ductility; dislocation density identified as the dominant contributor	Control: scan-strategy and orientation optimisation. Limitation: coupled texture/ dislocation/orientation effects
[33]	316L/LPBF	Mechanical anisotropy; build orientation, scan rotation and microstructure	Experimentally informed CPFEM reproduced direction-dependent tensile behaviour	Control: process-informed constitutive modelling. Limitation: model transferability requires validation beyond the investigated conditions
[34]	Ti-6Al-4V/hybrid PBF–DED	Microstructural and mechanical anisotropy; heat flow, build orientation, interface integrity and microstructural transition	Microstructural and mechanical assessment; direction-dependent strength and ductility	Control: thermal-history and interface control. Limitation: hybrid-architecture-specific response
[35]	SS316L and Ti-6Al-4V/AM stochastic structures	Structural stiffness anisotropy; strut orientation, morphology and build direction	Multi-directional testing; modified architectures reduced stiffness variation across ten loading orientations	Control: architecture modification. Limitation: geometry-specific behaviour

1.6. Surface Condition and SR

In AMed parts, SR refers to micro- and meso-scale deviations from the nominal surface generated by layer discretisation, partially fused or deposited material, stair-stepping, melt-track instability, support interaction and post-processing history [44]. SR is therefore both a geometric quality descriptor and a defect-sensitive performance variable, since it may influence dimensional accuracy, fatigue initiation, tribological behaviour, corrosion response, biological interaction and the effectiveness of subsequent finishing operations. Its magnitude and morphology depend on the AM process, material system, layer thickness, energy input, scan or deposition strategy, build orientation and surface-treatment route.

Representative AM studies illustrate how SR is governed by process parameters, material-deposition conditions, build orientation and post-processing, and how the resulting surface condition influences dimensional accuracy, mechanical performance and functional reliability. Giorleo and Ravelli [45] examined laser polishing as a post-processing route for improving the surface quality of parts produced by MJT. The process reduced roughness by 70%, reaching 4.5 μm, and produced more homogeneous surfaces despite minor accuracy loss. The study highlights laser polishing as a promising strategy for mitigating orientation-dependent surface irregularities in AM components. Bakhtiari et al. [46] investigated compressive behaviour in FFF-printed PLA using a Taguchi design to evaluate layer height, extrusion width, nozzle temperature and printing speed. Layer height most strongly governed compressive strength, modulus and SR, while failure was dominated by interlayer sliding and debonding, indicating clear optimisation pathways. Moura de Souza Soares et al. [47] evaluated SLM Ti6-Al4-V for implant applications, focusing on surface morphology and corrosion resistance. SEM and optical profilometry showed that hydrofluoric acid etching removed weakly adherent particles, reduced surface-related defects and improved corrosion behaviour, supporting acid treatment as a relevant post-processing route. Jiang et al. [48] developed a computational workflow for embedding SR and porosity defects into AM 2.5D lattice models and assessing their mechanical impact through FEM. Results showed stiffness degradation with increasing roughness, pore size and defect density, while highlighting algorithm-dependent biases relevant to future data-driven defect modelling strategies. Kamble et al. [49] proposed and experimentally validated a mathematical model for predicting SR in multi-jet sub-zero AM. The model incorporated droplet geometry, staircase effects and DPI-dependent overlap, outperforming previous approaches and showing that increased DPI improved surface finish, reducing average roughness by approximately 20%. Afroz et al. [50] examined the coupled influence of SR, pore size, pore location and loading ratio on fatigue life in L-PBF AlSi10Mg. The study showed that as-built fatigue performance is roughness-dominated, whereas subsurface porosity controls failure after machining or polishing, supporting XCT-informed fatigue-life assessment. Caggiano et al. [51] investigated wobbling-based laser polishing for SLM-produced Cr–Cu precipitation-hardening steel, aiming to reduce SR while limiting thermal degradation. The approach reduced roughness by 62–78% and supported CNN-based identification of optimal polishing parameters with 97–100% accuracy, strengthening automated post-processing optimisation. Grimm et al. [52] reviewed PBF surface analysis, identifying inconsistent terminology, weak measurement protocols, limited inter-study comparability and insufficient representation of complex topographies. The study positions surface quality as a critical determinant of PBF performance and underscores the methodological transition from conventional two-

dimensional roughness metrics towards three-dimensional surface metrology frameworks. Yildiz et al. [14] addressed the difficulty of reducing the inherently high SR of L-PBF 316L stainless steel while preserving tensile strength and ductility under different scanning-speed and post-processing conditions. It was shown that higher scanning speeds lowered as-built roughness, and fine brush polishing reduced Ra from 38.4 to 1.8 μm without the strength loss induced by machining.

Taken together, the AM-specific studies reviewed above provide complementary evidence linking processing conditions, surface morphology, post-processing and functional performance [53,54]. SR should therefore not be interpreted solely as a geometrical imperfection, but as a process-sensitive quality attribute with direct implications for fatigue behaviour, corrosion response, dimensional accuracy, post-processing requirements and functional performance. The literature broadly agrees that roughness is governed by layer thickness, build orientation, material-deposition stability, energy input and finishing strategy. Nevertheless, differences remain regarding the relative importance of roughness compared with internal defects such as porosity, particularly when as-built, machined and polished conditions are compared. A persistent limitation is the absence of sufficiently harmonised three-dimensional surface descriptors and measurement protocols capable of representing complex AM surface topographies consistently across processes, materials and applications.

1.7. Non-Destructive Testing (NDT) Methods

NDT and non-destructive evaluation approaches are increasingly important for assessing AMed components without impairing their subsequent structural or functional use. Depending on the expected defect population and component characteristics, computed tomography (CT/XCT), ultrasonic testing, thermography, optical inspection and related techniques can provide complementary information on internal discontinuities, surface condition and dimensional conformity [55,56]. Their effectiveness is not intrinsic to the inspection technology alone, but depends on defect size, morphology, orientation and location, together with the material system, component geometry, spatial resolution, calibration procedure and data-processing strategy.

Segovia Ramírez et al. [11] reviewed the application of NDT within AM and highlighted the need to match the inspection technique to the manufacturing process, material system and expected discontinuity type. Accordingly, NDT should be integrated within a broader quality-assurance workflow rather than treated exclusively as an end-of-process verification step. Where personnel qualification and certification are required for industrial NDT activities, ISO 9712:2021 specifies requirements for personnel performing methods including acoustic-emission, eddy-current, radiographic, thermographic, ultrasonic and visual testing [57]. The standard addresses personnel qualification and certification and should therefore be distinguished from AM-specific defect-acceptance or component-qualification criteria.

In addition to XCT, thermography, optical methods and conventional ultrasonics, several complementary electromagnetic and acoustic approaches are emerging for AM-specific inspection. Eddy-current testing (ECT) is particularly relevant to electrically conductive metallic AM components because local variations in conductivity, permeability and probe response may provide information concerning discontinuities, material-state variation and relative component quality. Recent literature has examined both *ex-situ* and *in-situ* ECT in PBF, DED and hybrid additive/subtractive systems, while also identifying temperature sensitivity, probe lift-off, component geometry and material-dependent electromagnetic properties as important implementation constraints. The potential integration of ECT with closed-loop monitoring and Digital-Twin (DT) architectures has also been recognised, although its application to AM remains less mature than established volumetric techniques such as XCT.

The present paper offers a critical review of defects in AMed parts, with particular emphasis on defect typologies, defect-formation mechanisms, and their implications for part quality, structural integrity and industrial reliability. The study is motivated by the need for a more integrated and analytically coherent account of the principal defect-related phenomena observed across AM processes, together with the inspection and analytical strategies used to identify, classify and interpret them. To that end, the review examines the origin, characteristics and consequences of the main defect classes, whilst also considering how process selection, material behaviour and manufacturing conditions influence defect occurrence, detectability and severity. Defects in AM are therefore addressed not as isolated anomalies, but as manifestations of an interconnected process–material–geometry system in which fabrication conditions, microstructural evolution and quality outcomes are closely interdependent.

From a mechanical engineering perspective, this broader interpretation is especially relevant where AMed parts are required to satisfy demanding functional, dimensional and reliability-related criteria. In such contexts, quality assurance and quality control should not be understood merely as end-stage verification activities. Rather, they must be regarded as integral components of the wider manufacturing system, influencing decisions related to process selection, parameter optimisation, qualification procedures, economic feasibility and the dependability of

the final component. Accordingly, the review adopts an engineering-centred perspective that gives particular attention to defect-detection methods, non-destructive evaluation, process-monitoring strategies and standardisation issues of direct significance for industrial implementation.

The paper is organised into six sections. Section 1, Introduction, establishes the context of the study, defines its scope and sets out the rationale for undertaking the review. Section 2, Method of Research, describes the review design, search strategy, study-selection criteria, and the procedure adopted to assess the relevance and quality of the literature considered. Section 3, Literature Review: Process–Material–Defect–Detection Synthesis, examines the principal defect typologies observed in AMed parts, the mechanisms governing their formation, and the inspection and monitoring approaches used for their detection and evaluation. Section 4, Discussion, analyses the main technical trade-offs, recurring methodological issues and the wider implications for industrial practice. Section 5, Conclusions, synthesises the principal findings of the review and identifies the most significant technical and practical considerations arising from the analysis. Section 6, Research Agenda and Future Directions, outlines prospective research directions, including the refinement of defect-detection methods, improved integration between process monitoring and quality assurance, and the further development of robust frameworks for the industrial qualification of AMed components. Collectively, these sections provide a critical and logically organised account of the current state of the art in defects in AMed parts and their detection.

2. Method of Research

This systematic review was developed through a structured and transparent literature-survey procedure informed by the PRISMA 2020 statement and its accompanying explanation and elaboration [58–60], with the objective of ensuring methodological consistency, traceability and reproducibility throughout study identification, screening, eligibility assessment and final inclusion. The bibliographic search was conducted in January 2026, covering peer-reviewed literature published between 1 January 2010 and 31 December 2025.

CrossRef was selected as the principal bibliographic source because it provides broad cross-publisher coverage of DOI-linked scholarly metadata across journals and publishing platforms relevant to AM, materials engineering, metrology, NDT and manufacturing quality assurance. This cross-publisher infrastructure enabled the retrieval of literature across the different AM process families and defect-related domains considered in the present review using a single, consistent bibliographic source [61].

The same source was used for bibliographic retrieval, DOI verification and metadata consolidation. Records obtained through the search procedure were subsequently integrated and processed using a bespoke MATLAB® routine developed to standardise bibliographic fields, identify duplicate records and support the successive screening stages. All potentially relevant records were then subjected to title, abstract and keyword screening, where these fields were available, followed by full-text eligibility assessment.

It should be noted that CrossRef is primarily a DOI and scholarly-metadata infrastructure rather than a curated citation-indexing database. Metadata completeness may therefore vary among publishers and individual records. This limitation was addressed through manual bibliographic verification and full-text assessment during the eligibility stage and is acknowledged as a methodological limitation of the present review.

2.1. Search Strategy and Information Sources

Building upon the PRISMA-based methodological framework outlined above, the literature search strategy was specifically configured to identify studies addressing defects in AMed parts, with particular emphasis on defect typologies, defect formation mechanisms, process-dependent quality limitations, and defect-detection methodologies, rather than broader contributions on AM considered in isolation. The search protocol was developed to ensure thematic specificity and to maximise the relevance of the retrieved literature using three complementary conceptual groups of keywords.

The first group focused on AM and defect-related terminology, including terms such as *"additive manufacturing", "3D printing", "manufacturing defects", "defect classification", "porosity", "cracking", "delamination", "anisotropy", "surface roughness",* and *"layer slippage"*. The second group addressed process categories and technology-specific contexts, incorporating terms such as *"material extrusion", "fused deposition modelling", "vat photopolymerisation", "material jetting", "sheet lamination", "powder bed fusion", "directed energy deposition",* and *"binder jetting"*. The third group concentrated on inspection, monitoring and analytical approaches, including *"defect detection", "non-destructive testing", "computed tomography", "3D scanning", "surface inspection", "process monitoring", "quality control", "part reliability",* and *"dimensional accuracy"*.

The Boolean search logic followed the general structure:

("Additive Manufacturing" OR "3D Printing" OR "Manufacturing Defects" OR "Defect Classification" OR "Porosity" OR "Cracking" OR "Delamination" OR "Anisotropy" OR "Surface Roughness" OR "Layer Slippage")

AND

("Material Extrusion" OR "Fused Deposition Modelling" OR "Vat Photopolymerisation" OR "Material Jetting" OR "Sheet Lamination" OR "Powder Bed Fusion" OR "Directed Energy Deposition" OR "Binder Jetting")

AND

("Defect Detection" OR "Non-Destructive Testing" OR "Computed Tomography" OR "3D Scanning" OR "Surface Inspection" OR "Process Monitoring" OR "Quality Control" OR "Part Reliability" OR "Dimensional Accuracy")

The Boolean expression was implemented within the CrossRef-based retrieval workflow developed for the study. Search terms were applied to the bibliographic metadata fields available through CrossRef and the resulting records were exported for subsequent consolidation and screening. Where individual records contained incomplete metadata, DOI information, title, authorship, publication year and publication source were cross-checked during the screening procedure. The complete search expression reported above was maintained throughout the retrieval procedure to ensure consistency across the final dataset.

Search terms were applied through the CrossRef bibliographic retrieval workflow, with matching based on the metadata available for individual records. Retrieved records were subsequently screened using titles, abstracts and keywords where these fields were available, followed by full-text assessment during the eligibility stage:

- Publication period: 2010–2025
- Document type: peer-reviewed journal research articles and review articles
- Language: English

CrossRef was deliberately selected as the principal source because its metadata infrastructure aggregates scholarly records directly from a broad range of participating publishers and therefore provides cross-publisher coverage that is well suited to a multidisciplinary review spanning AM processes, materials, defects, inspection methods and quality assurance. The use of a single retrieval infrastructure also ensured that the same search logic and metadata-processing procedure could be applied consistently across the entire dataset. Nevertheless, because CrossRef is not a curated citation index and metadata completeness can vary between records, all records considered for inclusion were subjected to manual relevance verification and full-text assessment.

Publications outside the predefined 2010–2025 systematic-search interval may be cited elsewhere in the manuscript for historical, methodological or definitional purposes but were not included within the quantitative systematic-review corpus.

These criteria were introduced to ensure that the review captured both foundational and contemporary developments in the study of defects in AMed parts, particularly concerning defect classification, process-specific defect generation, inspection methodologies, and the relationship between defect occurrence and component quality, while excluding publications outside the scope of AM defect analysis and detection.

2.2. Study Selection and Screening

The identification and selection of relevant studies were undertaken in accordance with the PRISMA 2020 guidelines, thereby ensuring methodological transparency, traceability and reproducibility throughout the review process. The initial bibliographic search was conducted primarily through the CrossRef database and supplemented by additional indexing platforms, most notably Dimensions.ai, yielding a substantial body of records spanning both foundational and recent contributions to AM defects, defect-detection methodologies and quality-assurance strategies. The large number of initial records reflects, in part, the extensive indexing coverage of CrossRef and related metadata repositories, which frequently contain duplicate entries arising from publisher-level indexing, early-access versions and overlaps between databases. CrossRef was selected as the principal bibliographic retrieval source because its metadata infrastructure provides broad cross-publisher coverage of DOI-linked scholarly publications across journals and publishing platforms relevant to AM, materials engineering, metrology, NDT and manufacturing quality assurance. The use of a single retrieval infrastructure also enabled the same search logic and metadata-processing procedure to be applied consistently across the multidisciplinary scope of the review. Additionally, it is primarily a DOI and scholarly-metadata infrastructure rather than a curated citation-indexing database, and the completeness of individual metadata fields may therefore vary among publishers and records. To mitigate this limitation, bibliographic information was verified during screening and potentially eligible studies were subjected to full-text assessment before final inclusion.

To address bibliographic redundancy, all records retrieved from CrossRef were consolidated using a bespoke MATLAB® routine. Duplicate identification was performed through a hierarchical procedure in which the DOI was used as the primary matching criterion whenever available. DOI strings were normalised before comparison by removing URL prefixes, unnecessary whitespace and differences in letter case. Where a DOI was unavailable or incomplete, potentially duplicated records were compared using normalised bibliographic information, principally article title, first-author information and publication year. Records presenting ambiguous similarity were retained for manual verification rather than being automatically discarded. The combined automated and manual procedure was therefore designed to minimise both duplicate retention and the erroneous removal of distinct publications. Following deduplication, the resulting set of unique records was subjected to title, abstract and keyword screening.

Screening and eligibility decisions were subsequently carried out according to predefined inclusion and exclusion criteria established prior to database interrogation, with the aim of minimising subjective bias and ensuring methodological consistency. Titles, abstracts and keywords were examined in order to assess their relevance to defects in AMed parts, with particular emphasis on defect classification, defect formation mechanisms, process-dependent quality limitations, NDT approaches, process-monitoring strategies and the relationship between defect occurrence and component performance. Particular attention was given to studies addressing porosity, cracking, delamination, anisotropy, SR, layer slippage, dimensional deviation, internal discontinuities and the applicability of inspection technologies to complex geometries, different material systems and distinct AM processes.

Publications lacking methodological clarity, those unrelated to defect generation or detection in AM, or studies that did not address part quality, inspection methods, process-induced discontinuities, defect-sensitive performance or process-specific defect mechanisms were excluded at this stage. A considerable proportion of the discarded literature concerned either general developments in AM with no substantive focus on defects, or broader materials and manufacturing studies without direct relevance to defect identification, monitoring, characterisation or mitigation.

Following application of the established eligibility criteria, the remaining publications were evaluated according to the predefined methodological and technical criteria described in Section 2.3. Journal impact, publication-venue prestige and citation frequency were not used as proxies for methodological quality or as criteria for study inclusion. The final corpus therefore reflects the methodological robustness, reporting transparency and relevance of individual studies to the objectives of the review rather than bibliometric characteristics of their publication venues. The complete numerical progression of the study-selection procedure, including the initial number of records retrieved, duplicate removal, title and abstract screening, full-text assessment, reasons for exclusion and final study inclusion, is reported in Appendix A in accordance with the PRISMA 2020 framework. Following completion of the screening and quality-assessment procedure, 134 publications were retained within the final systematic-review corpus.

During the review process, a recurrent challenge concerned the absence of fully standardised terminology within the AM defects literature. Identical or closely related phenomena are frequently described using different nomenclature, particularly in the case of defect types, process-induced discontinuities and inspection methods. For example, internal voids may also be reported as porosity, lack-of-fusion defects, gas pores or volumetric discontinuities, depending on the process, material system and analytical perspective adopted. Likewise, interfacial failure may be described as delamination, interlayer decohesion, poor bonding or layer separation. Comparable inconsistencies also arise in relation to inspection terminology, where expressions such as computed tomography, X-ray microtomography, volumetric imaging, three-dimensional scanning, surface digitisation and non-destructive evaluation are not always employed with strict definitional consistency. These variations required careful cross-verification of defect definitions, process contexts, measurement principles and reported outcomes during the classification and interpretation of the retrieved studies. Minor orthographic differences between American and British English further introduced bibliographic inconsistencies in indexed metadata.

The formulation of precise research questions constitutes a fundamental element of any systematic literature review, as it defines the analytical scope and conceptual direction of the investigation. To ensure internal coherence and close alignment with the objectives of the present study, the Population–Intervention–Comparison–Outcome–Context framework was adapted as follows:

- Population: Experimental, computational and review studies concerned with defects in AMed parts, including investigations of process-induced discontinuities, surface irregularities, internal flaws and defect-sensitive mechanical behaviour across different AM technologies.

- Intervention: Defect-detection, defect-characterisation and quality-assessment strategies applied to AMed components, including NDT, computed tomography, three-dimensional scanning, surface inspection, process monitoring and defect-classification approaches.
- Comparison: Comparative analyses between different AM processes, material systems, defect types and inspection techniques, particularly with respect to detection capability, sensitivity, dimensional resolution, applicability to internal and surface defects, and relevance to industrial quality control.
- Outcomes: Improved understanding of defect formation, classification and detection in AMed parts, together with the identification of persistent technical limitations, process-specific vulnerabilities, inspection constraints and unresolved research challenges affecting part quality and reliability.
- Context: Peer-reviewed academic publications addressing AM defects and their detection in engineering, materials and manufacturing applications.

The five overarching research questions presented in the Introduction were operationalised through the hierarchical subquestions shown in Table 7. These subquestions were used to structure literature extraction and to ensure that process conditions, material effects, defect mechanisms, performance consequences, inspection capability and emerging quality-assurance approaches were evaluated consistently throughout the review.

Table 7. Operational subquestions used for systematic evidence extraction and synthesis.

ID	Research Question
RQ1	What are the principal technical challenges affecting the identification, classification and reliable detection of defects in AMed parts across different AM processes?
RQ1.1	How do discrete manufacturing defects, geometrical deviations, surface-quality attributes and material-state or directional responses manifest across AM processes, and how do these different quality phenomena affect structural integrity, dimensional fidelity and functional performance?
RQ1.2	Which material characteristics, process conditions, geometric factors and build-related variables, including feedstock behaviour, thermal history, layer orientation, scanning strategy, energy input and part complexity, exert the greatest influence on defect formation, severity and detectability in AM?
RQ2	How do inspection, monitoring and analytical strategies determine the effectiveness of defect detection and quality assessment in AMed parts?
RQ2.1	To what extent do NDT methods, surface-inspection techniques and process-monitoring approaches improve defect identification, localisation, classification and confidence in the quality assessment of AMed components?
RQ2.2	What are the principal trade-offs associated with defect-detection workflows, particularly in relation to sensitivity, resolution, acquisition time, data-processing complexity, cost, operator expertise and industrial applicability?
RQ3	How do process parameters, inspection configurations and technology selection influence the reliability, repeatability and diagnostic capability of defect detection in AM?
RQ3.1	Which operational variables—such as layer thickness, build orientation, scan speed, laser power, extrusion conditions, sensor positioning, imaging resolution and acquisition setup—most strongly affect defect generation, defect visibility and inspection reliability?
RQ3.2	How do different AM technologies and inspection-system architectures influence the applicability, effectiveness and limitations of defect-detection strategies used to evaluate part quality?
RQ4	What recent developments in monitoring systems, analytical methodologies and digital inspection tools contribute to improved defect detection and quality assurance in AM?
RQ4.1	How can advanced approaches such as computed tomography, three-dimensional scanning, *in-situ* monitoring, machine-learning-assisted defect recognition and data-driven quality assessment support improved detection accuracy, efficiency and interpretative reliability?
RQ4.2	What technical, methodological and industrial limitations currently hinder the broader implementation of advanced defect-detection, intelligent monitoring and automated quality-assurance workflows in AM environments?
RQ5	What are the emerging research trends and future opportunities in the study and detection of defects in AMed parts?
RQ5.1	Which advanced concepts—such as intelligent process monitoring, hybrid inspection systems, machine-learning-assisted defect classification, DT-based quality control and integrated non-destructive evaluation frameworks—show the greatest potential for improving industrial reliability and defect-sensitive quality assurance?
RQ5.2	What key knowledge gaps remain regarding the integration of defect formation mechanisms, process monitoring, inspection technologies, defect classification and predictive quality-control methodologies in next-generation AM systems?

The systematic-review corpus was delimited primarily by AM process category and defect-related relevance rather than by a single material class. Studies concerning MEX, VPP, MJT, SHL, PBF, DED and BJT were eligible where they addressed defect formation, defect-sensitive quality attributes, performance consequences, inspection, monitoring or quality-assurance methodology. Metallic alloys, polymers, ceramics and composites were therefore included when they provided relevant evidence within these process-specific relationships. Material class alone was not used as either an inclusion or exclusion criterion.

The review does not attempt an exhaustive comparison of every material composition, alloy grade, polymer formulation, ceramic system or composite architecture reported in AM. Instead, material systems are treated as contextual variables within the process–material–defect relationship, allowing the synthesis to identify where reported behaviour is process-specific, material-dependent or transferable across AM routes. Likewise, lattice and architected structures are included only where they contribute evidence concerning defect generation, defect-sensitive performance or inspection capability.

The defect-related scope encompasses recurrent discontinuities and quality attributes including porosity and voids, lack of fusion, cracking, delamination or weak interfacial bonding, dimensional deviation, SR, anisotropic behaviour and layer slippage, together with other process-induced conditions where directly relevant to the analytical framework. The purpose of this delimitation is to provide sufficient breadth for cross-process comparison while avoiding the implication that the review constitutes an exhaustive material-by-material catalogue of AM defects.

The literature search procedure, illustrated in Figure 2, was implemented using structured Boolean queries designed to identify studies situated at the intersection of AM technologies, defect generation and defect-detection or quality-assessment methodologies. The search strategy therefore incorporated combinations of keywords related to AM and defect-related phenomena, including *"additive manufacturing", "3D printing", "manufacturing defects", "defect classification", "porosity", "cracking", "delamination", "anisotropy", "surface roughness"* and *"layer slippage"*, together with terms associated with process categories, such as *"material extrusion", "fused deposition modelling", "vat photopolymerisation", "material jetting", "sheet lamination", "powder bed fusion", "directed energy deposition"* and *"binder jetting"*. A third group of terms addressed inspection, validation and quality-related considerations, including *"defect detection", "non-destructive testing", "computed tomography", "3D scanning", "surface inspection", "process monitoring", "quality control", "part reliability"* and *"dimensional accuracy"*.

This structured search strategy enabled the targeted retrieval of scientific contributions directly concerned with defects in AMed parts, particularly studies addressing defect classification, defect formation mechanisms, inspection methodologies and quality-assessment strategies. It was designed to capture literature relevant to process-induced discontinuities, surface and internal defect characterisation, non-destructive evaluation techniques, *in-situ* and *ex-situ* monitoring approaches, and the comparative assessment of detection methods across different AM technologies. In this way, the search protocol supported a technically rigorous evaluation of the principal challenges, methodological trade-offs and emerging opportunities associated with achieving reliable defect identification, robust quality control and industrially relevant quality-assurance workflows.

An examination of the publication records retrieved from the CrossRef repository indicates a marked increase in scholarly output between 2010 and 2025, as illustrated in Figure 3. This upward trajectory reflects the growing academic and industrial interest in AM defects, particularly in relation to porosity, cracking, delamination, anisotropy, surface integrity, dimensional deviation and advanced defect-detection methodologies. The trend appears especially pronounced from the mid-2010s onwards, followed by a sustained period of high publication activity after 2020, thereby suggesting the consolidation of defect-sensitive quality assessment as an increasingly mature and strategically important area of research and industrial practice.

Collectively, these developments underscore the growing recognition that defect identification and control are critical to the reliability, qualification and broader industrial adoption of AM. Advances in inspection technologies, process-monitoring methodologies and analytical workflows are increasingly regarded as essential for improving defect detectability, strengthening quality assurance and enhancing confidence in the structural and functional integrity of AMed components.

To improve transparency regarding the composition of the final literature dataset, Table 8 summarises the main analytical dimensions represented in the selected corpus, including the number of included studies, AM process categories, defect categories and detection technologies considered. This summary complements the PRISMA-based selection procedure by clarifying the breadth of the evidence base used for the subsequent descriptive, taxonomic and critical synthesis.

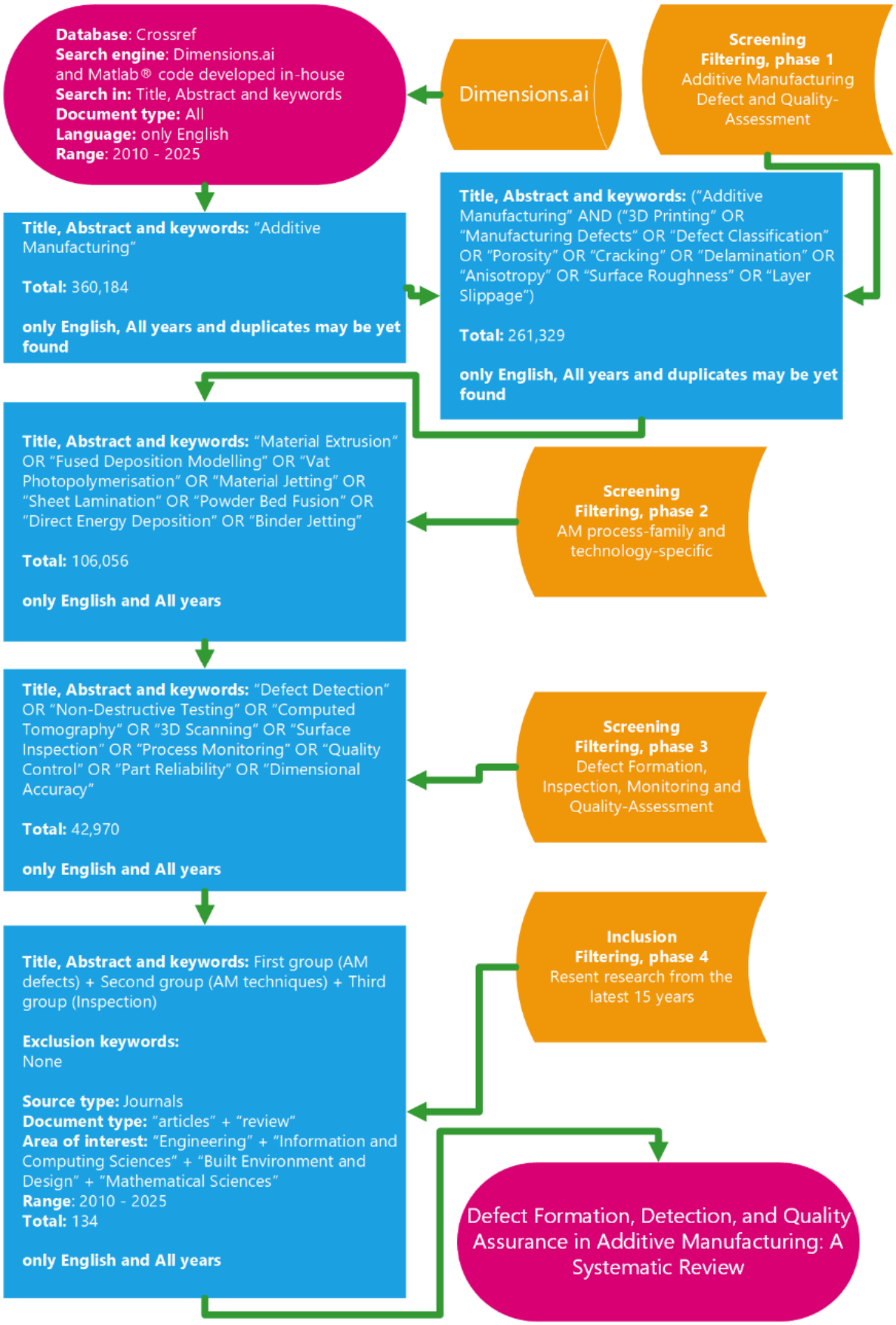


Figure 2. PRISMA-based multi-stage screening and study-selection procedure applied to the literature on defects in AMed parts, focusing on defect typologies, defect-detection methods, process monitoring, and quality-assurance strategies.

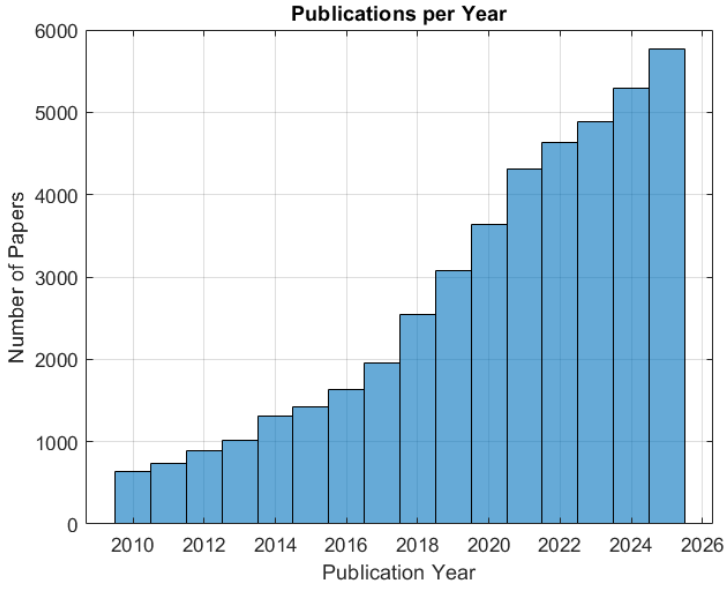


Figure 3. Annual distribution of publications retrieved from the CrossRef database concerning defects in AMed parts and their detection.

Table 8. Summary of the final literature dataset represented in the review.

Dataset Dimension	Representation in the Final Corpus	Analytical Relevance
Included studies	134 publications retained after the final inclusion stage	Defines the evidence base used for the systematic synthesis and subsequent thematic classification
AM process categories	7 process families: MEX, VPP, MJT, SHL, PBF, DED and BJT	Ensures coverage of the principal ISO/ASTM AM process categories and supports cross-process comparison
Predominant defect and quality-phenomenon categories	Discrete discontinuities: porosity/voids, lack of fusion, cracking, delamination/weak bonding; geometrical deviations: dimensional deviation, distortion and layer misalignment; surface-quality attributes: SR; material-state/directional phenomena: residual stress, heterogeneity and anisotropic behaviour.	Enables consistent separation of manufacturing discontinuities, geometrical deviations, surface conditions and material-state responses while supporting cross-process comparison.
Detection and inspection technologies	CT/XCT, optical scanning, surface profilometry, ultrasonic testing, thermography, metallography/SEM and *in-situ* monitoring	Clarifies the principal inspection approaches represented in the literature and supports comparison of defect-detection capability
Main analytical focus	Defect formation mechanisms, defect classification, detection capability, inspection limitations, process monitoring and quality-assurance implications	Links the selected dataset to the review objectives and research questions

2.3. Study Selection and QA

The appraisal of methodological quality constitutes an essential component of any systematic review, since the credibility of the resulting synthesis depends directly upon the reliability, transparency and analytical robustness of the studies included. In the present investigation, a structured Quality Assessment (QA) procedure was established to evaluate the scientific rigour, reporting clarity and technical relevance of each selected publication. The assessment strategy was conceived as a multidimensional framework capable of capturing not only academic robustness, but also the extent to which the reported findings contribute meaningfully to the understanding and advancement of defect analysis and defect-detection strategies in AMed parts.

The QA framework was organised into four equally weighted domains, each intended to examine a distinct dimension of methodological quality and scholarly contribution. The criteria were informed by established principles of systematic review design and were applied through a three-level ordinal scoring system, in which Yes was assigned 1, Partly 0.5, and No 0. The four evaluation domains were defined as follows:

- Research Design and Conceptual Coherence (25%)—assessing the clarity of the study aims, the suitability of the research methodology, and the extent to which the investigation is supported by a coherent scientific and technical rationale.
- Definition of the AM and Defect-Assessment Framework (25%)—examining whether the AM process, material system, defect type, part geometry, inspection method, monitoring configuration and relevant processing or measurement parameters are described with sufficient precision, including details necessary

for reproducibility, such as build orientation, layer thickness, energy input, feedstock characteristics, sensor configuration, imaging conditions, resolution, calibration procedures or defect-classification criteria.

- Methodological Rigour and Analytical Transparency (25%)—evaluating the robustness of the experimental, computational or analytical procedures, the adequacy of validation methods, and the consistency with which defect identification, interpretation and reporting are conducted.
- Technological and Industrial Relevance (25%)—determining the degree to which the findings contribute to the practical understanding of defects in AMed parts, particularly in relation to defect detectability, quality assurance, dimensional fidelity, structural integrity, process reliability and suitability for industrial implementation.

The four QA domains were equally weighted at 25% of the overall assessment. For each domain, a score of 1 was assigned when the corresponding criterion was fully satisfied, 0.5 when it was partially satisfied and 0 when it was not satisfied. The overall QA score was calculated according to Equation (1):

$$QA_{score}(\%) = 25 \cdot (Q_1 + Q_2 + Q_3 + Q_4), \tag{1}$$

where Q_1 denotes Research Design and Conceptual Coherence, Q_2 denotes Definition of the AM and Defect-Assessment Framework, Q_3 denotes Methodological Rigour and Analytical Transparency, and Q_4 denotes Technological and Industrial Relevance. The resulting overall score therefore ranged from 0 to 100%. A score of 60% was established as the standard acceptance threshold for inclusion in the detailed analytical synthesis. Studies achieving a QA score of ≥60% were considered to satisfy the methodological-quality requirements of the review. Studies scoring between 50% and <60% were classified as borderline and underwent an additional full-text assessment focused on determining whether identified shortcomings reflected incomplete reporting rather than fundamental methodological weakness. Studies scoring <50% were excluded from the analytical corpus.

QA was undertaken independently by five authors of this paper. Each evaluator applied the four-domain scoring framework to the eligible full-text publications before the resulting assessments were compared. In borderline cases, inclusion required agreement that the publication provided sufficiently reliable and technically relevant evidence to support the objectives of the review. Journal impact factor, publication-venue prestige and citation frequency were not included within the QA score and were not used to determine study inclusion. QA was based exclusively on the methodological, reporting and technical characteristics of each individual publication. Figure 4 presents the distribution of QA scores obtained for the evaluated publications, providing an overview of the methodological-quality profile of the studies considered during the systematic-review procedure.

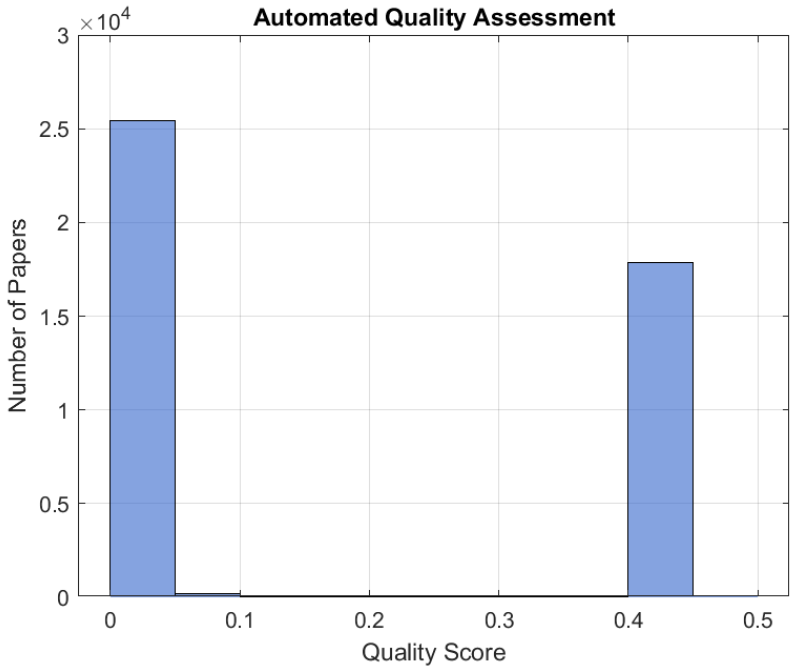


Figure 4. Distribution of quality-assessment scores for publications evaluated during the systematic-review procedure.

As illustrated in Figure 5, the geographical distribution of authorship and institutional affiliation within the reviewed literature indicates a marked concentration of research activity in countries with established strengths in AM, materials engineering, non-destructive evaluation and advanced production technologies. China emerges as the

most prominent contributor, followed by the United States of America, India and the United Kingdom, with Germany and Turkey also occupying significant positions within the scholarly output on AM defects, defect detection and part-quality assessment. This distribution reflects the scientific and industrial relevance of defect-sensitive quality assurance in sectors such as aerospace, biomedical engineering, automotive manufacturing, tooling and other high-value applications in which structural integrity, dimensional fidelity and process reliability are critical.

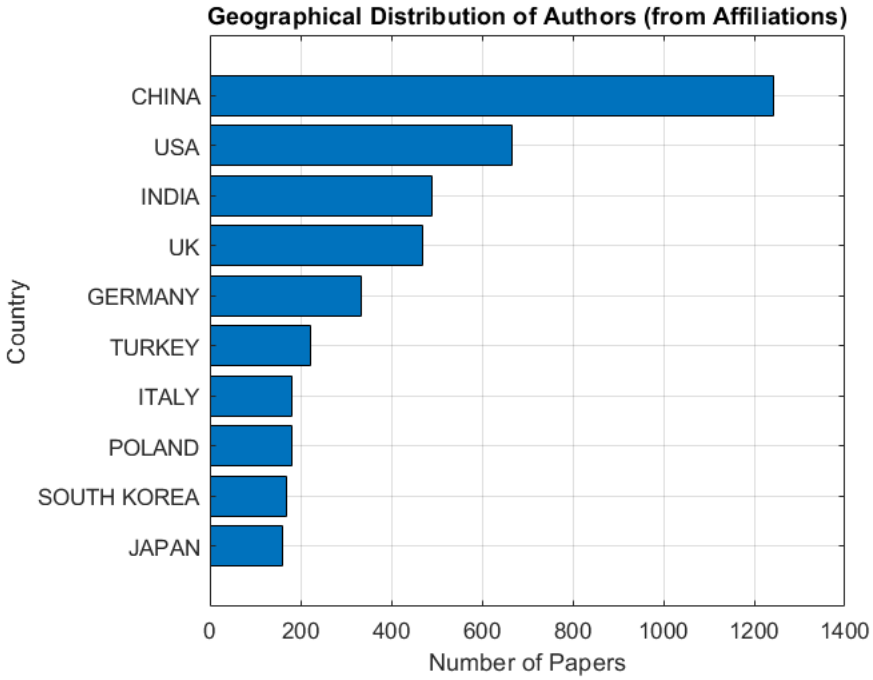


Figure 5. Geographical distribution of authors' institutional affiliations within the publications included in the systematic review of defects in AMed parts, with particular emphasis on defect classification, process-induced defect formation, inspection methods, non-destructive evaluation, and quality-assurance approaches relevant to part integrity and reliability.

This geographical pattern is of particular significance, as it indicates that research on defects in AMed parts is not confined to a narrow group of countries traditionally associated with manufacturing innovation. Rather, the field exhibits an increasingly international research profile, reflecting the global importance of improving defect detectability, process understanding, inspection robustness, quality-control reliability and the broader industrial qualification of AMed components. Collectively, these trends suggest that defect analysis and detection in AM have developed into strategically important and internationally distributed areas of research, supported by sustained contributions from both established and emerging centres of technological expertise.

2.4. Descriptive Analysis and Taxonomic Synthesis

The descriptive synthesis of the final body of literature reveals a technically diverse and progressively expanding field of research, characterised by the growing convergence of AM, materials engineering, metrology, non-destructive evaluation, process monitoring and data-driven quality-assessment methodologies. The selected studies were classified according to their technological orientation, defect focus, and level of experimental, computational or integrated analytical depth, thereby enabling the identification of the principal trajectories along which contemporary research on defects in AMed parts is developing. Overall, the reviewed literature may be understood as converging around two closely related research domains.

(1) Defect formation, classification and process-specific behaviour: This domain encompasses investigations concerned with the origin, morphology and distribution of defects arising across different AM routes. Attention is given to the influence of processing conditions on defect generation, severity, localisation and persistence. Studies within this category examine the effects of variables such as energy input, thermal gradients, feedstock characteristics, layer orientation, scanning strategy, deposition stability, curing conditions and part geometry on the development of porosity, cracking, delamination, anisotropy, SR, dimensional deviation and other process-induced discontinuities. Research in this area is directed towards

improving process understanding, defect classification and causal interpretation, whilst clarifying the relationship between manufacturing conditions and part integrity.

(2) Defect detection, validation and quality assessment: The second domain concerns the identification, characterisation and evaluation of defects through inspection, monitoring and analytical procedures. This body of work includes studies focused on NDT, computed tomography, three-dimensional scanning, surface inspection, *in-situ* and *ex-situ* monitoring, and quality-control methodologies, together with investigations into their influence on defect detectability, classification reliability, dimensional verification and confidence in the integrity of the manufactured component. These approaches are intended to overcome the limitations of conventional post-process inspection and to support the reliable industrial qualification of AMed parts in demanding applications.

This classification highlights the inherently multidisciplinary character of current research on defects in AM, in which manufacturing science, materials engineering, metrology, inspection technology, data analysis and digital quality-assurance frameworks intersect in order to address the complex thermal, geometric, material and procedural challenges associated with part quality and reliability. Across the reviewed literature, four principal thematic directions may be distinguished.

(1) Defect mechanisms and quality-limiting phenomena: A substantial proportion of the literature is devoted to the identification, characterisation and mitigation of recurring defects affecting AMed parts, including porosity, lack-of-fusion features, cracks, delamination, anisotropy, rough surfaces and dimensional inaccuracy. These studies seek to clarify the relationships between process conditions, material behaviour and defect evolution, with the objective of improving component quality and reducing defect-sensitive performance degradation.

(2) Optimisation of process parameters and defect-sensitive repeatability: Another major line of investigation concerns the optimisation of operational variables to improve process stability, reduce defect formation and enhance reproducibility. Emphasis is placed on the selection of process conditions capable of controlling thermal history, interlayer bonding, geometrical accuracy, surface integrity and internal soundness. In this context, increasing attention is also devoted to the repeatability and reproducibility of AM processes across different material systems, machine platforms and build configurations.

(3) Inspection capability, validation and industrial applicability: Recent studies increasingly examine the capability of different inspection and validation procedures to assess internal and surface defects, dimensional conformity and practical part reliability. This includes analyses of computed tomography, three-dimensional scanning, NDT and process-monitoring techniques, as well as investigations into their diagnostic capability, technical limitations and suitability for industrial implementation.

(4) Intelligent monitoring, automated detection and digital quality assurance: A further area of development involves the use of computational modelling, machine-learning-assisted defect recognition, intelligent monitoring systems and data-driven quality-assessment tools to improve inspection efficiency and interpretative robustness. These studies address defect classification, image-based inspection, sensor fusion, anomaly detection and predictive quality control, thereby contributing to more reliable, scalable and intelligent quality-assurance systems for AM.

Across the reviewed studies, several recurrent technical gains are reported, including:

- improved understanding of defect formation and process–defect relationships;
- enhanced detectability of internal and surface discontinuities;
- greater confidence in dimensional verification and part-quality assessment;
- improved interpretation of defect-sensitive performance and structural integrity;
- better integration of inspection and monitoring within AM workflows;
- broader industrial applicability through more robust quality-control and quality-assurance strategies.

Notwithstanding these advances, the literature also identifies several persistent challenges that continue to limit broader industrial implementation. These include the difficulty of achieving consistently low defect levels across different processes and material systems, the complexity of correlating process parameters with defect evolution, the limited standardisation of inspection and quality-assessment procedures, the cost and technical constraints associated with high-resolution non-destructive evaluation systems, and the challenge of integrating process monitoring, defect detection and qualification procedures into coherent and economically viable manufacturing workflows. Additional constraints arise from the variability of reported process conditions, defect definitions, inspection settings, validation criteria and performance metrics across different technologies and application domains.

The three-stage screening procedure adopted in the present review, in accordance with the PRISMA 2020 framework, commenced with an initial appraisal of titles, abstracts and keywords in order to identify publications relevant to AM defects, defect generation, defect detection and quality assessment. This preliminary screening was followed by detailed full-text assessment designed to verify conformity with the predefined inclusion criteria, with particular emphasis placed on methodological rigour, technical depth and relevance to the objectives of the review.

Only peer-reviewed journal articles were retained for the final analysis. Publications written in languages other than English, grey literature, conference abstracts lacking adequate methodological detail, and studies without sufficiently transparent analytical procedures were excluded. The resulting dataset therefore constitutes a carefully curated and scientifically robust body of literature, providing the evidential foundation for the analytical and interpretative framework developed in the present study.

3. Literature Review: Process–Material–Defect–Detection Synthesis

The literature is synthesised in this section according to the analytical framework established in Table 4. The seven principal AM process categories constitute the primary organisational level, while material systems are treated as contextual variables influencing defect-generation mechanisms and resulting performance. Each process category is examined using the sequence: material and process context → defect-generation mechanism → resulting defect morphology → performance consequence → detection and monitoring capability → mitigation strategy and evidence limitation. This mechanism-centred structure enables comparison across AM processes while distinguishing process-specific behaviour, material-dependent effects and relationships that recur across multiple manufacturing routes.

3.1. Material Extrusion (MEX)

In MEX, defect formation is governed primarily by the interaction between feedstock rheology, extrusion conditions, raster strategy, layer geometry, thermal history and interlayer bonding. The reviewed evidence identifies inter-bead voids, incomplete bonding, dimensional deviation, warpage, surface irregularity and layer slippage as recurrent manifestations, although their relative importance varies with material formulation and deposition conditions [62–64]. These defects should therefore be interpreted through their underlying bonding and deposition mechanisms rather than as independent geometrical imperfections.

Different papers have proposed classifications for defects based on factors such as surface or internal defects. Agarwala et al. [62] suggested a binary classification of defects, dividing them into surface and internal defects. Surface defects included issues like support staircase effects, curve approximation errors, top and bottom surface aspects, and defects related to the deposition delay when head motion starts or stops. Internal defects had various origins such as voids generated by abrupt movement changes of the deposition head, voids caused by turning or bonding weakness between adjacent paths, filament slippage in the feeding system, and non-uniform deposited filament diameter.

Penumakala et al. [63] in their recent work focused on thermoplastic polymer composite-based reviews, demonstrating how these composites are reinforced to enhance mechanical properties based on application requirements. They also explored factors influencing defect reduction. Papazetis and Vosniakos [64] conducted Taguchi experiments linked to an artificial neural network to evaluate the influence of layer thickness, material flow, deposition head velocity, and plane orientation on part shape conformity to its CAD model. They identified defects such as ‘Deformed edges’ and ‘Under-extrusions’ in their study. It is mentioned that other works by different authors also exist but do not lead to the same level of defects considered in the paper discussed. However, the mechanical aspects of the resulting application should be highlighted.

Within MEX, layer slippage is treated in this review as a deposition-induced geometrical misalignment rather than as a universal manufacturing-defect class. It refers to the unintended positional offset of one or more deposited layers relative to the intended toolpath or preceding material, resulting in a departure from the nominal component geometry. Its occurrence may be associated with inadequate interlayer adhesion, unstable extrusion, inappropriate temperature control, deposition-speed variation, mechanical positioning errors or material-dependent flow behaviour.

The engineering significance of layer slippage depends on its magnitude and location. At low levels, it may primarily appear as dimensional or surface non-conformity; at greater levels, the associated misregistration may generate local stress concentrations, weak interfaces or loss of load-bearing continuity. In such cases, the geometrical deviation may coexist with discrete defects such as interfacial decohesion or delamination. This distinction is maintained throughout the present review so that the primary manifestation—layer misalignment—is not conflated with the structural defects or performance losses that it may subsequently induce.

In the pursuit of mitigating layer slippage in Fused Deposition Modelling (FDM), researchers have conducted studies to explore innovative approaches and methodologies. This section delves into some relevant studies that have contributed to the understanding and development of mitigation strategies for layer slippage.

(1) Sells et al. [65] investigated the impact of printing parameters on layer adhesion in FDM. The research investigates how variations in temperature, layer height, and extrusion rate influence the occurrence of layer slippage. Insights from this study provide practical considerations for optimising printing parameters to mitigate the risks of slippage.
(2) Chen and Lu [66] conducted a comprehensive study in 2013 focusing on the role of material properties in layer slippage. By systematically analysing the influence of material composition, viscosity, and bonding characteristics, the study contributes valuable information on selecting materials that minimise the occurrence of layer misalignments.
(3) Bhatt et al. [67] explored the integration of advanced cooling strategies to mitigate layer slippage. The study investigates the effects of controlled cooling on layer adhesion and provides insight into how cooling mechanisms can be optimised to enhance the overall integrity of FDM-printed parts.
(4) Kim et al. [6] took a novel approach by investigating the potential of Artificial Intelligence (AI) in predicting and preventing layer slippage. By employing machine learning algorithms, the research aims to identify patterns and correlations in printing data to proactively mitigate the risks associated with layer misalignment.
(5) Rana and Fayazbakhsh [68] addressed the difficulty of developing a fully integrated in-process defect-detection system for MEX, capable of repeatably identifying embedded gaps with quantitative accuracy during fabrication. Layer-wise laser scanning accurately captured intentional internal gaps, delivering low variability and error, and outperforming phased-array ultrasonic testing for gap-width evaluation.
(6) De La Rosa et al. [69] focused on the difficulty of achieving reliable closed-loop defect detection in fused filament fabrication, particularly the real-time identification and correction of stringing, over-extrusion, under-extrusion and weak infill. A CNN-based closed-loop inspection framework was developed and achieved 92.86% validation accuracy and enabled dynamic G-code modification to correct extrusion-related defects during printing.
(7) Ashebir et al. [13] addressed the difficulty of reliably detecting multi-scale defects in material-extruded fibre-reinforced thermoplastic composites, particularly where material heterogeneity limits the sensitivity of conventional NDT. A critical review was delivered linking defect classification, advanced NDT, machine-learning-assisted inspection, and self-sensing composites to improved structural reliability and aerospace applicability.
(8) Gajjar et al. [70] delved into the difficulty of clarifying how layer thickness, raster angle, feed rate, and nozzle temperature jointly govern tensile response, SR, void formation and interlayer debonding in FFF-printed PLA. It was demonstrated that reduced layer thickness, lower raster angle, slower feed rate and higher nozzle temperature improved tensile performance, surface finish and interlayer bonding in FFF-printed PLA.
(9) Özel et al. [71] addressed the difficulty of identifying local and accumulated FFF defects in real time by integrating physics-informed understanding with CNN-based image classification for in-process quality monitoring. A physics-informed CNN framework was developed and successfully classified defective and non-defective FFF layers with high accuracy, supporting timely defect identification and reduced material wastage.

These relevant studies collectively contribute to the knowledge base surrounding layer slippage in FDM and offer diverse perspectives on mitigation strategies. By examining the methodologies and findings of these studies, manufacturers and researchers can glean valuable insights for implementing effective measures to address and mitigate layer slippage challenges in their AM processes.

3.2. VAT Photopolymerization (SLA, DLP, DLS, CDLP and Others)

VAT photopolymerization (VPP) is the first-ever introduced 3DP process, which utilises a light source to perform polymerisation reactions in photosensitive materials. Several industrial sectors, including mechanical, medical sciences, electrical/electronics, etc., have adopted this [72]. The ceramics and structures manufactured by VP technology, including stereolithography apparatus (SLA), digital light processing (DLP), and lithography-based ceramic manufacturing (LCM), have the advantages of high precision, high surface quality, high density, among others. In that sense, VP has gradually become the most widely adopted AM technology for advanced ceramics and structures [12].

According to the geometry and performance-related characteristics of defects, we divided defects into the following types: Pore defect, Crack defect, Delamination effect, Surface defect and other defects. Digital light processing (DLP) is quite like stereolithography (SLA), except that SLA uses laser beam technology to completely

cure the layers by point-to-point tracing the geometry and thus provides better print quality and accuracy [12]. The dimensional accuracy of VP AMed ceramics is affected by the resolution of the light source and the sintering shrinkage rate. The SR is mostly determined by the stair effect, part position towards the lamination direction, the tilt angle and the layer thickness. To eliminate the stair effects and improve the manufacturing resolution, the light intensity and exposure time should be decreased while ensuring the curing thickness [12].

As Zhang et al. [12] summarised, pore defects are the most common type and are also the origin of other defects such as crack defects, which greatly affect the density and mechanical properties of VP AMed ceramicsf.

Pore formation in VP AMed ceramics can be classified into two: residual pores (or shrinkage pores) and sintered pores. On the one hand, the raw material used in VP is a photosensitive ceramic slurry composed of ceramic powder, dispersant, diluent, stabiliser, etc. Air will inevitably be mixed in the slurry preparation process.

During the VP process of the green body, there is a relative shearing motion between the scraper and the ceramic slurry, so it is easy to mix air at the edge of the scraper and form bubbles, and finally pore defect formed in the green body. During the sintering process, if the driving force necessary for the fusion and elimination of pores in the green body surpasses both the grain growth and the maximum sintering driving force, the fusion and discharge become exceptionally challenging. Consequently, the pores shrink and persist in the sintered ceramics, resulting in the formation of residual pore defects.

Zhang et al. [12] through Salmoria et al. [73] showed that post-curing treatments including ultraviolet, microwaves and conventional heating on polymer green parts increased mechanical properties like tensile strength. Once a crack is formed during the manufacturing process, it will spread along the layer interface, significantly affecting the mechanical properties of ceramics. The generation of crack defects is the result of the combined effect of material physical properties and residual stress. There are differences in the formation mechanism of crack defects in various materials and manufacturing methods. The post-processing methods used to improve pore defects cannot effectively eliminate the crack defect. Therefore, the control and elimination of crack defects have always been one of the difficulties in the field of VP.

On the one hand, the non-ceramic components in VP AMed green body are gradually softened, oxidised, and decomposed into small molecular organic compounds during the debinding process. These organic compounds with high saturated vapour pressure will escape from the green body as gas. However, if there are not enough exhaust passages in the green body, these gases will form a certain pressure difference between the outer surface and the interior of the green body, which will lead to the occurrence of a crack defect. On the other hand, the oxidation process and pyrolysis of the organic matter are endothermic; thermal stress due to temperature difference will be formed inside and outside the green body, which will also lead to the generation of the crack defect, as shown in Figure 6.

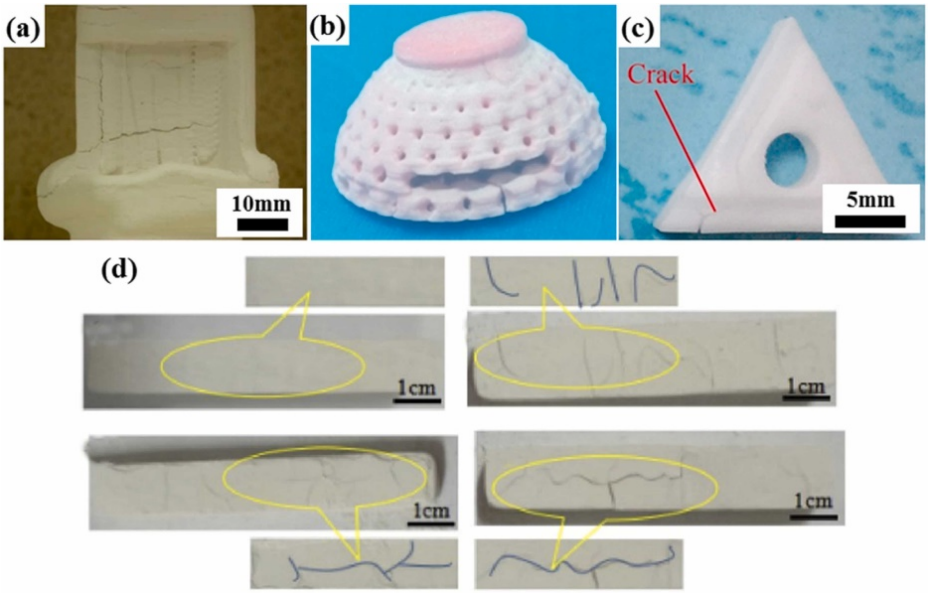


Figure 6. Typical crack defects in VP AMed ceramic: (**a**) illustrating cracking in SiO_2 ceramic; (**b**) illustrating a β-TCP ceramic component; (**c**) illustrating an Al_2O_3 ceramic component with a crack initiation; (**d**) illustrating debinding-related defects in a Si_3N_4 ceramic.

An interface will be formed between the layers, which is also the weakest part of the entire part. When subjected to tensile stress on the surface, it is easy to produce a delamination defect at the interlayer junction after

the debinding and sintering process, thus causing the entire part to fail. On the other hand, in the case of uneven heating inside and outside, delamination defects are easily generated inside due to different thermal shrinkage of materials, which is also a potential threat to the part.

For the top-down DLP process, there is bonding stress between the layers of the green body in the building direction (z-axis) due to the compressive stress between the motor-driven moulding platform and the photosensitive slurry. During the debinding and sintering process, the interlayer bonding stress is released at the weak point of the interlayer bonding, causing the formation of a crack defect.

When the light intensity and exposure time are insufficient during the VP process, the low polymerisation between interlayers may lead to the formation of delamination defects. In the debinding and sintering process, the shrinkage between the upper and bottom layers is uneven because the green body is limited by the bearing plate. The upper layer tends to shrink due to heating, while the bottom layer limits its deformation, resulting in residual stress exceeding the interlayer bonding force and the formation of a delamination defect.

In addition, the defects in VP AMed ceramics also include deformation, compositional defects, structural collapse, residual stress, and other defects. For example, deformation refers to defects such as warpage caused by bonding or other stresses between VP AMed ceramics and the substrate. Compositional defects mainly come from the oxidation of non-oxide materials or other chemical reactions during the high-temperature post-treatment process, resulting in impurity defects [12].

In terms of defects, the pore is one of the most common defects due to the formation in every fabrication stage, which can reduce the mechanical property. The crack defect is another common challenge of VP, which mainly forms in the debinding process. Delamination defects often appear in AM technologies due to the layer-by-layer manufacturing strategy, which results in anisotropic behaviour. The surface defects such as the layer-by-layer appearance of AM affect the fabrication resolution and are not preferable. Other defects, such as residual stress, should also be controlled carefully in the thermal process. To increase the mechanical properties of the VP AMed ceramics, various control methods for the corresponding defects must be presented based on the understanding of defect types and formation mechanisms [12].

Table 9 summarises representative studies published between 2010 and 2025, together with the corresponding processing parameters and principal outcomes, thereby providing a consolidated overview of the evolution of VPP as an AM route. The reader may observe that the quality and performance of vat-photopolymerised parts are strongly dependent on exposure conditions, layer thickness, build orientation, resin characteristics, and post-processing operations such as washing, support removal, and post-curing, which collectively govern dimensional accuracy, surface quality, degree of conversion, and final mechanical behaviour.

Table 9. Representative studies on vat-photopolymerised materials and components.

Ref	Material/Route	Defect or Quality Phenomenon—Mechanism/Variables	Detection/Characterisation—Quantitative or Principal Evidence	Mitigation/Control—Remaining Limitation
[74]	Al_2O_3/ stereolithography	Deformation and cracking; drying and debinding conditions	Density/mechanical characterisation; 99.3% relative density and hardness comparable with conventionally shaped ceramics	Control: PEG-assisted drying + two-step debinding. Limitation: NR
[75]	Ceramic/VPP	Recoating defects; defect variability and limited training data	Dual-branch deep-learning monitoring; F1 = 0.89 at 54.01 fps	Control: real-time image-based monitoring. Limitation: small-scale dataset and defect variability
[76]	Photopolymer resin/laser VPP	Mechanical anisotropy; polymerisation kinetics and critical curing energy	Anisotropy quantification; faster initial polymerisation and lower critical energy associated with greater anisotropy	Control: resin/curing-condition selection. Limitation: strong resin dependence
[77]	Al_2O_3/ stereolithography	Process-chain defects; cleaning, debinding, sintering and anisotropic shrinkage	Microstructural/defect assessment; sharp-edged mechanically competitive ceramic parts demonstrated.	Control: post-processing optimisation. Limitation: defect evolution spans multiple processing stages
[78]	Ceramic systems/VPP	Sedimentation, viscosity, light scattering, shrinkage and anisotropic deformation	Critical review; quantitative performance NR	Control: material/process development including pre-ceramic, multimaterial and nanocomposite routes. Limitation: scale-up and coupled material/process constraints

3.3. Material Jetting (MJT)

MJT is a process of generating droplets repetitively. It has a similar operational principle to that of the inkjet printing technique. In the MJT process, the liquid phase material is first collected in a chamber. This material is then jetted into the desired coordinates in small droplets. In this process, the volume, velocity and frequency of the

droplets are important. In other words, the base material is directly deposited droplet by droplet to generate a 3D physical object [79].

MJT process has the advantage of printing multi-material parts, enabling technology for a wide range of applications. As reviewed by Liu and Sing [80], the current shortcomings of MJT technology are divided into two principal areas: material and technology. The layer-by-layer method has gaps and defects that can have a significant impact on the final performance of certain elastomeric materials, such as fatigue life.

On the other hand, the raw materials used in MJT technology are photosensitive; the mechanical properties of the finished product could potentially deteriorate over time.

Precise and stable drop formation based on optimised waveforms has been widely reported, although the development of advanced waveforms for newly developed inks is still very time-consuming and could be accelerated, for instance, by combining drop-watching and AI techniques [81]. As cited by Elkaseer et al. [81], commonly occurring issues in MJT such as shrinkage, layer height inconsistency, oxygen inhibition and gas dissolution in the fluid are outlined, and existing and potential solutions for mitigating these problems, such as ink recirculation, in-loop layer height correction, layer levelling device, curing at inert environment, etc. are pointed out. Furthermore, poorly cured layers may lead to migration of unreacted materials, low mechanical properties and geometrical inaccuracy

As investigated by Giorleo and Ravelli [45], the laser polishing of photopolymers printed with MJT achieved a good result, reducing the roughness up to 70%. In addition to that, the laser process eliminated any orientations caused by the additive process mechanism. His results show that the strong use of MJT technology does produce tools and parts with homogeneous surface finish, albeit with some loss of accuracy caused by absorption of thermal energy. Figure 7 shows the base setup for their experiments.

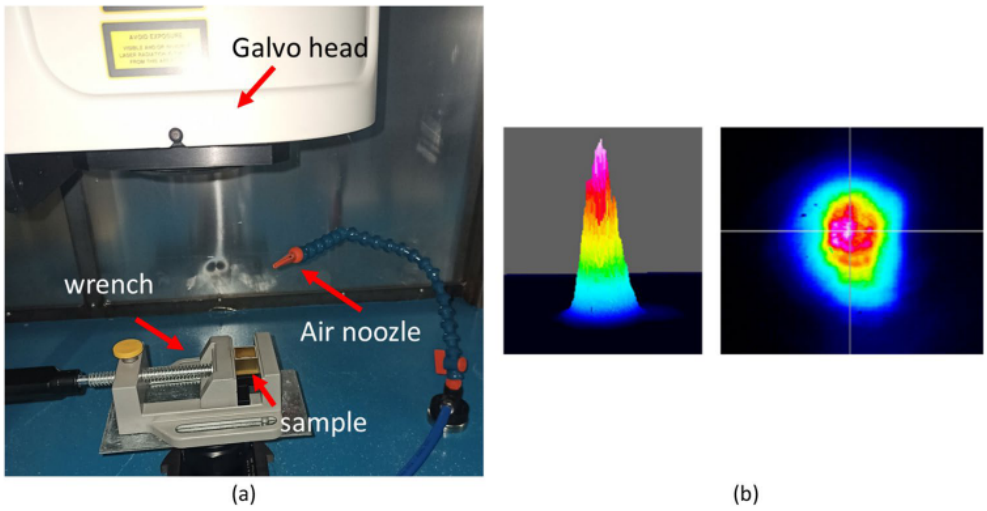


Figure 7. Laser polishing set-up: (**a**) experimental arrangement showing the galvo head, assist-air nozzle and specimen positioning; (**b**) laser-beam power distribution showing the Gaussian intensity profile [45].

When it comes to printing delicate structures, shrinkage of the parts results in warpage of the UV-cured layer. A weak interface between layers, constant filament diameter variations, and underflow of material that results in filament slippage cause fractures in the material, which results in the untimely reduction of the part's overall strength.

As Shrestha and Manogharan [82] concluded, there are four variables in this process to maximise rupture strength; they are: Binder Saturation, Layer thickness, roll speed, and feed-to-powder. He also concluded that the saturation level and feed-to-powder ratio were critical parameters. Also, a higher percentage of volume for binder and densification of powder at higher ratio of feed-to-layer thickness ratio improves both powder-binder interaction and densification.

Studies from de Pastre et al. [26] and Vu et al. [83] found that printing orientation of multi-material sandwich structures is shown to have an important impact on the material fracture resistance. Layers printed in the x-y plane exhibit better fracture resistance properties.

Table 10 summarises representative studies published between 2010 and 2025, together with the corresponding processing parameters and principal outcomes, thus offering a consolidated overview of the evolution of MJT as an AM route for advanced metallic components. The reader may observe that MJT is strongly dependent on feedstock formulation, droplet generation and deposition stability, layer-wise consolidation behaviour, and post-

processing operations, making subsequent thermal treatment, densification, and finishing stages decisive for dimensional accuracy, defect minimisation, surface integrity, and final functional performance.

Table 10. Representative studies on materials and components manufactured by MJT.

Ref	Material/Route	Defect or Quality Phenomenon—Mechanism/Variables	Detection/Characterisation—Quantitative or Principal Evidence	Mitigation/Control—Remaining Limitation
[84]	PolyJet/glossy cylindrical features	Dimensional and geometrical deviation; process- and feature-dependent shape error	Dimensional/geometrical analysis; improved size, cylindricity and coaxiality	Control: DfAM re-parameterisation and local geometric compensation. Limitation: process/feature dependence
[85]	PolyJet/airfoil geometries	SR and distortion; build orientation	Surface measurement + CFD; horizontal build improved surface quality and roughness increased aerodynamic drag	Control: build-orientation selection. Limitation: geometry/application-specific
[86]	PolyJet/glossy parts	SR prediction; glossy-surface behaviour not adequately represented by existing models	Regression model; lower prediction error than previous mathematical models	Control: pre-process roughness prediction. Limitation: model/surface-condition dependence
[87]	Photoacrylic resin/PolyJet	Surface-topography variation; resin dependence	Stylus and optical/focus-variation comparison; replica-assisted focus variation identified as viable	Control: appropriate metrology selection. Limitation: material-dependent surface response
[88]	Multi-MJT	Mechanical-property variation; UV overexposure and build-layout effects	Exposure modelling + mechanical characterisation; overexposure altered modulus and hardness	Control: UV-dose/build-layout management. Limitation: layout- and material-dependent response

3.4. Sheet Lamination (LOM, SDL, LLM, SLCOM, CBAM)

Sheets of materials are successively rolled, and layer outlines are cut by a laser. Then, a roller bonds the current layer to the previous one. SHL is then adapted to produce composite parts and heterogeneous materials by adding prefabricated material between layers [26].

The SHL process can be classified into the following two categories:

(1) Laminated object manufacturing and Ultrasonic consolidation. Laminated object manufacturing (LOM) is one of the oldest AM processes.
(2) Objects are made from prefabricated layers; therefore, this method is fast compared to pixel-based AM methods. However, the traditional LOM method is not able to work on multi-material structures. This limits the kind of structures that can be produced using LOM.
(3) For polymers, ceramics, and paper-based materials, the heated roller activates thermos-active glue spread over the previous layer. For metal-based materials, bonding is mainly performed by ultrasonic waves emitted by a sonotrode roller resulting in the layer fusing by vibration and friction response of the metal sheet [67].

Some of the common defects presented by this method are variations in form derived from the staircase effect and part variation in size due to varying gas flow rate, overall part shrinkage or microstructural waviness. Bhatt et al. [67] found there were 3 important constant factors in the lamination process: the accuracy error of the manufactured part, the bonding strength between layers and the speed of the operation. In his experiment he found out that part accuracy is affected largely by sheet cutting, the placement of externally produced components, and the sheet thickness. The sheet cutting errors were present mostly due to the burns/heat marks on the cutting edge and the accuracy error of the manipulator.

The most common defects are roughness either due to powder deposition, appearance of fractures, cracks, or holes. The balling effect is also common due to improper cooling rates, which also contribute to warping. The sheet thickness is responsible for the stair-stepping effect in the final part. Such stair-stepping effect is seen in most of the AM processes, and it is responsible variation between the actual part surface and the CAD model [67].

Peel strength is an important parameter in SHL-based AM processes. It is a function of the quality of the bonding between the layers governed by the layer materials, their surface finish, the type of adhesive used, the thickness of the adhesive bond, the pressure applied on the bonding surface, the time allowed for bonding and any defects in the bond (e.g., air bubbles, dirt). The quality of the bonding will control the resulting structural strength of the components manufactured using it.

Manufacturing time for a typical AM process depends on the speed of the material deposition process. In Bhatt et al. [67] study, the manufacturing time was limited by the maximum speed of each process. Anisotropy phenomena are somewhat related to scan direction and layer orientation. Temperature and powder conditioning have an influence on part heterogeneity [26].

Table 11 summarises representative studies published between 2010 and 2025, together with the corresponding processing parameters and principal outcomes, thereby providing a consolidated overview of the evolution of SHL as an AM route for engineering components. The reader may observe that SHL is strongly influenced by sheet material characteristics, bonding conditions, layer alignment, cutting accuracy, and interlayer consolidation behaviour, making subsequent finishing operations decisive for dimensional accuracy, defect mitigation, surface integrity, bond quality, and final structural performance.

Table 11. Representative studies on materials and components manufactured by SHL.

Ref	Material/Route	Defect or Quality Phenomenon—Mechanism/Variables	Detection/Characterisation—Quantitative or Principal Evidence	Mitigation/Control—Remaining Limitation
[89]	LOM/material NR	SR; surface angle, layer thickness, cutting profile and penetration depth	Geometrical roughness-prediction model + experimental validation; credible agreement with measurement	Control: geometry/process-parameter selection. Limitation: focused on surface condition
[90]	UAM/material systems reviewed	Bond integrity, microstructure and mechanical response; UAM process parameters and interfacial conditions	Literature synthesis; quantitative effect of NR	Control: process-parameter and post-treatment optimisation. Limitation: cross-study/ process variability
[91]	UAM/material systems reviewed	Bond quality and deformation; pressure, amplitude, weld speed and temperature	Critical review; quantitative effect NR	Control: process-parameter/post-processing optimisation. Limitation: unresolved parameter–microstructure–property relationships
[92]	UAM laminated interfaces	Interfacial fracture; mixed normal–shear loading	Dovetail testing + cohesive-zone FEM; fracture prediction with 10.1% error	Control: interface-aware modelling/design. Limitation: calibration specific to evaluated interfaces/loading conditions
[93]	UAM/*in-situ* quality monitoring	Weld anomalies/process-condition disturbances	Thermal imaging + deep learning; >96% classification accuracy and up to 99.14% across reported scenarios	Control: predictive *in-situ* QA. Limitation: generalisation beyond tested scenarios NR

3.5. Powder Bed Fusion (PBF-EB/M, PBF-LB/M, PBF-LP/P, PBF-IrL/P)

Powder bed technologies use fine particles of different nature (metallic, ceramic, or polymeric) as feedstock. These technologies allow the production of very complex geometries using a heat source to fuse the powder particles layer by layer, transforming the feedstock into a solid part. This fusing process happens under a protected atmosphere so that the feedstock is processed in the right conditions, avoiding oxidation and therefore making it possible for the powder to be used again after each build.

Parts made using this method also suffer from the "staircase" effect of layers, where defects have an influence on overall dimensions and form. The varying powder grain size also contributes to machine errors, inconsistent tap density, part shrinkage and microstructural waviness. All these lead to geometrical inaccuracy and geometrical deformation.

It is probable that any contamination from the gaseous byproducts and reflected energy from the bed of powder impacts the local beam spatial energy distribution, causing poor geometrical accuracy [10].

According to Parry et al. [94] typically, porosity and geometric defects (distortion and low dimensional accuracy) can be related to the electron/laser beam scanning or deflection system. SR is a characteristic of any variation of this process, that is a consequence of poor laser configurations, powder deposition irregularities, quality of powder and the surface orientation. Oxide formation is a major concern for AM built Al-alloys since the oxide formation increases the surface tension of the molten Al which promotes balling effect [95]. The density of the powder bed also affects the quality of the printing layer with denser layers making fusion steadier and more continuous [96].

According to Mostafaei et al. [10] research, when parts are close to each other, heat distribution and dissipation are governed by the spacing between walls such that partial melting of the powder particles increases and they adhere together on the solidified surfaces, leading to increased SR. Due to a large thermal gradient, strong anisotropy is generated after solidification, influenced by scan and layer orientation. Various degrees of heterogeneity in the material due to powder conditioning and solidification conditions.

The microstructure, due to the high solidification rate is one of the concerns in AM parts is the growth of columnar grains that grow along the build direction which can lead to the growth of cracks and anisotropy [10]. Powder composition, impurities, and inclusions with feedstock materials can be transferred to the final part and deteriorate mechanical properties and corrosion resistance. Therefore, it is essential to evaluate potential powder-related defects and remedies to improve build quality. Residual stresses in AM parts are a governing factor for part cracking and delamination susceptibility.

Table 12 summarises representative studies published between 2010 and 2025, together with the corresponding processing parameters and principal outcomes, thereby providing a consolidated overview of the evolution of PBF as an AM route for advanced metallic components. The reader may observe that PBF is strongly dependent on powder characteristics, energy-input conditions, scan strategy, layer-wise melting and consolidation behaviour, and post-processing operations, making subsequent heat treatment, stress relief, densification, and surface finishing decisive for dimensional accuracy, defect minimisation, microstructural control, surface integrity, and final functional performance.

Table 12. Representative studies on materials and components manufactured by PBF.

Ref	Material/Route	Defect or Quality Phenomenon—Mechanism/Variables	Detection/Characterisation—Quantitative or Principal Evidence	Mitigation/Control—Remaining Limitation
[97]	316L/LPBF	Porosity and lack of fusion; energy density and hatch spacing	Taguchi analysis + XCT; energy density and hatch spacing identified as dominant variables	Control: processing-window optimisation. Limitation: NR
[98]	Metallic systems/LPBF	Lack-of-fusion porosity; high-dimensional process-parameter interactions	Thermo-fluid simulation + active learning + symbolic regression; compact predictive relationship obtained	Control: model-guided parameter selection. Limitation: broader transferability requires validation
[99]	INCONEL® 718/LPBF	Porosity; volumetric energy density	Helium pycnometry/Archimedes comparative metrology; optimal VED region associated with low porosity and higher tensile strength	Control: VED optimisation. Limitation: porosity estimate depends on measurement method
[100]	Metals/LPBF	Porosity detection; stochastic/subsurface defect formation, noise and process complexity	Review of *in-situ*/*ex-situ* methods; sensor capabilities and detectable scales compared	Control: multi-sensor monitoring. Limitation: subsurface sensitivity, noise and process complexity
[101]	AlSi10Mg/LPBF	Internal porosity; weak defect echoes and SNR constraints	Laser ultrasonics + FEM; localisation and depth estimation of sub-millimetre internal defects	Control: model-assisted ultrasonic inspection. Limitation: weak echoes/limited SNR
[102]	Metallic systems/LPBF	Spatter-driven keyhole/LOF porosity; hatch sequence	XCT + microscopy; spatter-impact metric linked to porosity and hatch strategy	Control: hatch-strategy optimisation. Limitation: sequence-sensitive behaviour
[103]	Material NR/LPBF	SR as an indicator of part quality	Surface-roughness characterisation; quantitative result NR in the current manuscript	Control: NR. Limitation: quantitative details must be retrieved from the original study before further claims are added
[104]	Material NR/LPBF	Multiscale quality variation; subsurface phenomena and complex AE signatures	Acoustic emission + synchronised IR; AE signatures linked to build failures, SR and microstructural heterogeneity	Control: multimodal *in-situ* monitoring. Limitation: signal interpretation/ defect attribution

3.6. Directed Energy Deposition (DED)

DED processes are commonly categorised into laser-based DED, arc-based DED and electron-beam DED depending on the kind of energy used [26]. The overall dimensional inaccuracy and deformations are commonly related to the size and temperature of the melt pool, inefficient deposition rate and cooling rate.

Suárez et al. [105] affirmed that to achieve the final product's dimension in DED, the process must be repeated layer by layer and this may cause inaccurate deposition or insufficient deposition of material in each layer. Also, due to the layer-by-layer binding nature, the final surface quality is poor or partial bonding may happen. Svetlizky et al. [106] found that high cooling rates and thermal gradients were the main reason for residual stresses and distortions.

Lalegani Dezaki et al. [107] reported that laser power is one of the principal process parameters governing material properties in DED, while horizontal and vertical build orientations generally exhibited higher strength than inclined or perpendicular orientations. Svetlizky et al. [106] through their study concluded that the high SR of DED'ed parts may result mainly from:

- Sticking to the surface of partially melted powder particles due to low heat input and large powder particles.
- Stair stepping effect, which limits all layered manufacturing processes.
- Splashing of molten material, i.e., SR is determined by various material feedstock, part design, processing, and post-processing conditions and variables.

Different temperature gradients and different solidification rates upon layer stacking influence the morphology of the material. The presence of trapped gas, or the formation of gas bubbles also affect the part's porosity [26]. Lalegani Dezaki et al. [107] in their study concluded that grain elongation in build orientation is

high in DED products when their structure is roughly uniform. Stiffness, strength, and ductility under tensile strength are decreased when anisotropy in grain structure corresponds to the poor particle distribution. However, post-processing techniques such as machining and HIP can be used to reduce anisotropy.

Grain morphology, crystallographic texture, lack-of-fusion defects, phase transformation, heterogeneous recrystallization are the main factors that affect anisotropy in the DED process. It has also been reported that, in the DED process, support structures are required for the manufacture of complex geometries.

However, due to the attachment of support structure to the main part, deformities and non-uniform surface may occur which affect residual stresses and mechanical properties.

Higher density leads to better stiffness and lower porosity in final products. In contrast, agglomeration may happen due to the excess of metal particles in specific areas [107]. The cooling rates and thermal gradients disparities make up much of the causes of cracks, residual stresses in the part formation. These cause an overall reduction in strength and fatigue life of the material.

M. Dezaki found that laser power is the energy source that has the greatest effect on material properties. The printed sample has higher strength in vertical and horizontal directions [61].

During the DED process, heating and cooling play an important role in solidification in various zones. Poor adhesion and bonding in small sections and complex features cause residual stress between layers while the lower strength is seen in the perpendicular orientation.

To sum up, in Dezaki's view Laser beam diameter and laser power were the most important elements. Results showed that by increasing scanning speed, layer thickness increased while layer thickness is related to power density and powder feed rate as well. Layer thickness, SR, and processing time were considered as main dependent parameters. Figure 8 shows some of the parameters in DED manufacturing.

Table 13 summarises representative studies published between 2010 and 2025, together with the corresponding processing parameters and principal outcomes, thereby providing a consolidated overview of the evolution of DED as an AM route for advanced metallic components. The reader may observe that DED is strongly dependent on feedstock characteristics, energy-input conditions, deposition strategy, melt-pool stability, layer-by-layer material consolidation, and post-processing operations, making subsequent heat treatment, stress relief, machining, and surface finishing decisive for dimensional accuracy, defect minimisation, microstructural control, surface integrity, and final functional performance.

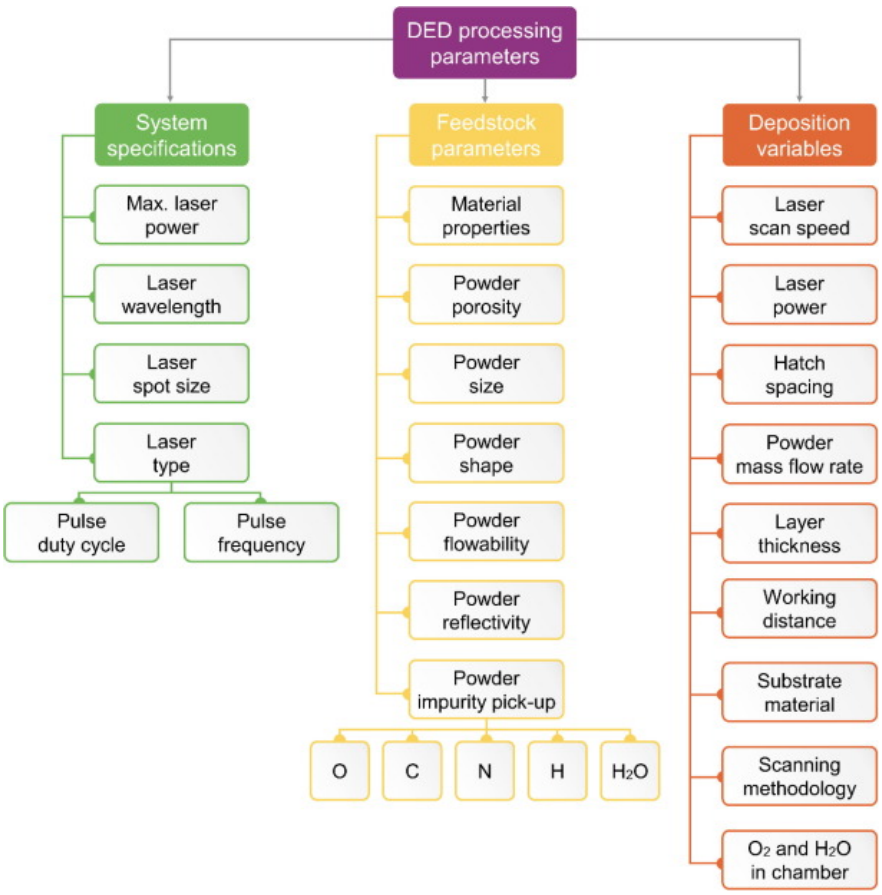


Figure 8. DED process parameters diagram [108]

Table 13. Representative studies on materials and components manufactured by wire arc additive manufacturing (WAAM) within the directed energy deposition (DED) process family.

Ref	Material/Route	Defect or Quality Phenomenon—Mechanism/Variables	Detection/Characterisation—Quantitative or Principal Evidence	Mitigation/Control—Remaining Limitation
[109]	Material NR/WAAM	Porosity, LOF, cracking and residual-stress distortion; coupled thermal/process instabilities	Critical review; quantitative evidence NR	Control: process-specific prevention strategies. Limitation: quantitative comparability NR
[110]	WAAMcomponents	Defect detectability degraded by pronounced SR	Radiographic testing + 3D laser scanning; roughness-induced image artefacts reduced and deliberately introduced defects more clearly resolved	Control: surface-geometry-informed radiographic correction. Limitation: quantitative detection resolution NR
[111]	Stainless steel/WAAM	Porosity, cracks, LOF, residual stress, distortion and surface degradation; process-parameter interactions	Critical review; quantitative evidence NR	Control: integrated process/defect-control strategies. Limitation: study-level quantitative comparability limited
[112]	Material NR/WAAM	Lack of fusion; inadequate bead overlap, low CMT heat input, arc deflection and substrate cooling	Process evaluation; 73% reduction in LOF defects	Control: combined CMT, CMT + weaving and P-GMAW strategy. Limitation: process/ configuration-specific

3.7. Binder Jetting (BJT)

BJT involves successive steps which introduce defects of different natures. For each layer, the binder is selectively projected onto the powder bed before being dried by a heat lamp. To reinforce the part properties, a sintering step is performed on the printed green part.

In addition, as a 3D printing method with the lowest energy input, BJ has the advantages of lower thermal residual stress, higher productivity, and better powder recyclability [113].

Geometrical and dimensional defects can happen due to dimensional inaccuracy of the printed part relative to the defined geometry and deformation effect such as shrinkage.

This dimensional inaccuracy can be due to the uneven layer spread, printing speed, grain size or not perfect sintering conditions. According to Chen et al. [96], particle segregation leads to different amounts of binder saturation and thermal conductivity during sintering of the BJ-printed parts. Ultimately, this leads to nonuniform deformation at the part level.

SR can be related to layer thickness, binder saturation, particle size and sintering process. When the binder infiltrates the powder, surface energy minimization drives it into separate spheres (balling) [114]. The larger size and better wettability between the powder and binder are beneficial for reducing the occurrence of balling [113]. Figure 9 shows some of those surface defects.

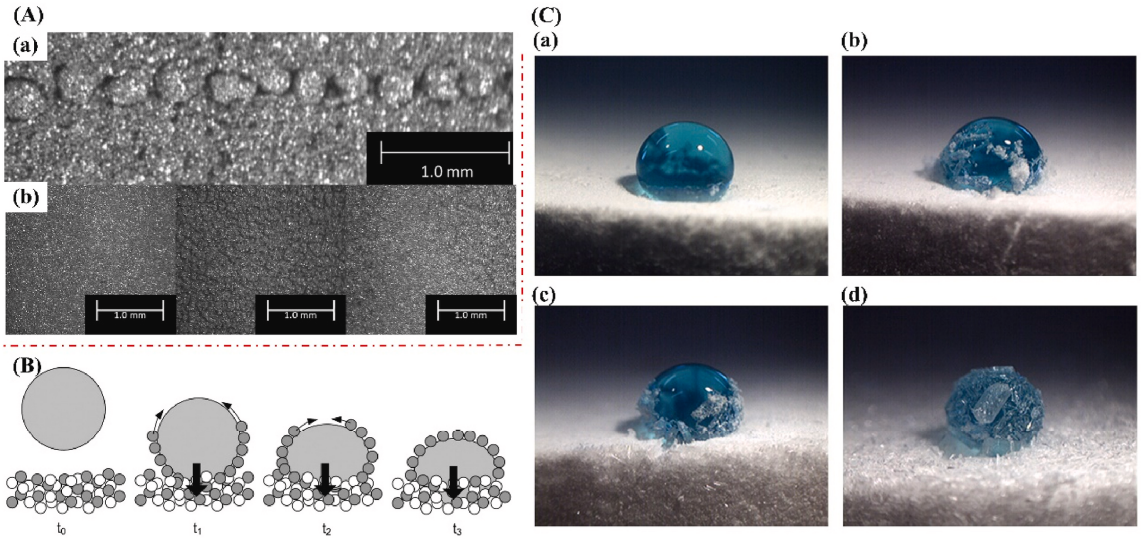


Figure 9. Binder–powder interaction and balling behaviour in binder jetting: (**A**) representative surface morphologies associated with balling, showing (**a**) pronounced localised agglomeration and irregular surface features and (**b**) a comparatively more uniform powder-bed surface; (**B**) schematic representation of hydrophobic-particle spreading over a liquid droplet, from the initial droplet–powder contact at t_0 through progressive particle

attachment at t_1 and t_2 to the formation of a particle-covered droplet at t_3; (**C**) experimental sequence illustrating powder attachment to a liquid droplet: (**a**) initial droplet resting on the powder bed, (**b**) onset of powder adhesion to the droplet surface, (**c**) progressive particle accumulation around the droplet and (**d**) formation of a substantially powder-covered droplet. [113].

Part orientation, layer thickness, particle shape and densification lead to a porous part. During the sintering process, the presence of "surface cracks" in each layer may lead to the formation of enclosed voids within the printed object [113]. Difference in binder saturation, caused by particle size mixing, takes effect on the overall mechanical properties of the part. It's important to control the binder distribution and saturation. These aspects also relate to layer thickness and density, part of the powder distribution strategy.

As Guo et al. [115] wrote, the most common defect, namely nozzle clogging. This defect is determined by the properties of the binder. Nozzle clogging can lead to incomplete print graphics and cracks inside the printed parts, thus deteriorating the mechanical properties of the printed parts. Citing Zhao et al. [113], the process of binder curing inevitably generates a thermal stress. The uneven temperature field of the heating lamp leads to "curling". According to Lima et al. [116] et al., shrinkage only occurs at the layer height, and the layer width is limited by the substrate or previously deposited layer. This causes transverse tensile stress during the drying process. If these stresses exceed the strength of the powder bed, cracks occur.

Table 14 summarises representative studies published between 2010 and 2025, together with the corresponding processing parameters and principal outcomes, thereby providing a consolidated overview of the evolution of BJT as an AM route for advanced metallic components. The reader may observe that BJT is strongly dependent on powder characteristics, binder formulation and saturation, layer deposition quality, printing strategy, debinding and sintering behaviour, and subsequent post-processing operations, making thermal treatment, densification, infiltration or hot isostatic pressing where applicable, machining, and surface finishing decisive for dimensional accuracy, defect minimisation, microstructural control, surface integrity, and final functional performance.

Table 14. Representative studies on materials and components manufactured by BJT.

Ref	Material/Route	Defect or Quality Phenomenon—Mechanism/Variables	Detection/Characterisation—Quantitative or Principal Evidence	Mitigation/Control—Remaining Limitation
[117]	Metallic systems/BJT	Incomplete densification and dimensional deviation; powder spreading, binder–powder interaction, sintering and shrinkage	Literature synthesis; ten metallic systems reported to exceed 90% relative density with suitable optimisation/sintering	Control: material/process and sintering optimisation. Limitation: cross-material variability
[118]	Powder-bed system/BJT	Surface ridges; aggressive forward-rotating roller compaction and compaction thickness	Surface-defect characterisation; ridge accumulation increased with layer count and depended on compaction thickness	Control: compaction-strategy optimisation. Limitation: quantitative acceptance threshold NR
[119]	Binder-jetted steels	Porosity; infiltration-induced heterogeneity	Immersion ultrasonics + XCT validation; wave-speed and attenuation maps revealed spatial porosity distributions	Control: complementary ultrasonic/XCT assessment. Limitation: heterogeneity complicates quantitative qualification
[120]	SiC/BJT	Green-part cracking/integrity loss; compaction thickness	SEM and density/microstructural assessment; greater compaction increased packing/green density but revealed a density–integrity trade-off	Control: compaction-thickness optimisation. Limitation: improved density can increase crack risk

3.8. Cross-Process Inspection and Detection Strategies:

Whereas Sections 3.1–3.7 examine inspection within individual AM process contexts, this section compares detection technologies across process families. The objective is not to rank inspection methods universally, but to assess how their applicability changes with defect morphology, material response, component geometry and the type of quality information required. Particular attention is therefore given to the distinction between volumetric, surface, dimensional and process-monitoring information and to the limitations governing the transfer of inspection capability between AM applications.

As the pursuit of flawless AMed parts intensifies, the reliance on sophisticated tools for defect detection becomes paramount. This section delves into the array of tools and technologies employed to identify and characterize defects in AM processes. From advanced imaging techniques to NDT methods, the discussion aims to provide readers with a comprehensive overview of the diverse tools available for defect detection, setting the stage for an in-depth exploration of their applications and effectiveness. In the realm of AM, ensuring the production of flawless parts has become a paramount goal. This pursuit has led to the adoption of sophisticated tools and techniques for defect detection, encompassing both internal and external facets of manufactured

components. Defect-detection methods for AM components must address two fundamentally different inspection domains: internal volumetric integrity and external geometrical or surface conformity. The following comparison therefore focuses on AM-specific evidence concerning XCT/μCT for internal defect characterisation and optical or three-dimensional scanning for external geometry and surface assessment [121–124].

3.8.1. Axial Tomography and 3D Scanning as Non-Destructive Techniques:

X-ray computed tomography (CT/XCT), including micro-computed tomography (μCT), provides volumetric information on the internal structure of AMed components and is particularly relevant to the characterisation of porosity, lack-of-fusion regions, cracks and other internal discontinuities. Renzo et al. [121] applied μCT to an additively manufactured Ti-6Al-4V specimen to investigate defect-sensitive crack evolution under combined loading. Sun et al. [125] reviewed high-energy XCT for non-destructive dimensional metrology of large advanced-manufactured metallic components, while more recent AM-specific studies have addressed the metrological classification, repeatability and uncertainty associated with XCT-based porosity evaluation [126,127]. Mönter et al. [128] further examined the extension of conventional CT towards time-resolved 4D analysis, highlighting both opportunities and algorithmic limitations for industrial NDT.

Three-dimensional optical scanning addresses a different inspection domain. Rather than resolving internal volumetric discontinuities, it is principally suited to the assessment of external geometry, dimensional deviation, warpage and accessible surface condition. Kladovasilakis et al. [129] presented an integrated quality-control and inspection solution for AM processes, while Martin et al. [130] demonstrated LiDAR-based real-time geometrical inspection for large-scale AM. Du et al. [131] applied 3D scanning and dimensional measurement to dental metal AM, and [132] reviewed recent developments in *in-situ* three-dimensional surface-topography monitoring across AM processes. Collectively, these studies show that volumetric tomography and surface-oriented three-dimensional scanning are complementary rather than interchangeable inspection approaches.

3.8.2. Evidence-Based Comparison of Inspection Capability

XCT/μCT and three-dimensional surface scanning provide fundamentally different but complementary information for AM quality assurance. XCT offers volumetric access to internal features and enables three-dimensional characterisation of pores, lack-of-fusion regions, cracks and internal geometrical features. Its principal limitations arise from the trade-off between spatial resolution and component size, acquisition and reconstruction time, material attenuation, segmentation methodology and measurement uncertainty [125,126,128]. These limitations become particularly relevant when quantitative pore morphology or defect-size distributions are used for qualification decisions.

By contrast, optical, structured-light and LiDAR-based three-dimensional scanning are primarily suited to rapid non-contact evaluation of external geometry, dimensional conformity, warpage and accessible surface topography [125,128,130,131]. Their major advantages include relatively rapid acquisition, large-area coverage and potential integration with *in-situ* or automated inspection workflows. However, because such approaches depend on optical access to the component surface, they cannot directly characterise internal volumetric defects.

The choice between the two approaches should therefore not be framed as a universal ranking of inspection efficacy. XCT is preferred when internal defect morphology and volumetric integrity are the principal quality concerns, whereas three-dimensional scanning is more appropriate when external geometry, surface conformity or dimensional deviation is the primary inspection objective. For complex AM qualification tasks, combining both approaches may provide a more complete representation of component integrity than either method used independently. Because XCT/μCT and three-dimensional scanning address different inspection domains, their performance should be interpreted in relation to the type of information required rather than through a single measure of overall efficacy. XCT/μCT is primarily suited to the volumetric characterisation of internal discontinuities and internal geometry, whereas three-dimensional scanning is principally used for external geometry, dimensional conformity and accessible surface assessment. Table 15 summarises the principal differences between the two approaches in terms of inspection objective, representative AM applications, strengths, limitations and supporting evidence.

Table 15 consolidates representative inspection evidence using common fields describing the target defect or quality condition, material/process context, reported quantitative capability, implementation characteristics and principal limitations. The values shown represent the conditions of the cited studies and should not be interpreted as universal detection limits.

Table 15. Representative evidence on the capability and implementation constraints of selected inspection and monitoring approaches for AM quality assurance.

Inspection Approach	Representative AM/Material/Target	Reported Quantitative Capability	Acquisition/Integration Characteristics	Principal Limitation
XCT/µCT [123,126,129,130]	Metallic AM; Ti alloy, Al alloy and Ni-based systems; internal porosity, cracks and internal geometry	Wilbig et al. [126]: isotropic voxel size ≈ 6 µm; relative standard uncertainty in porosity analysis up to 12% for LMJ, 38% for PBF-LB, and 70–89% for DED depending on pore population and image quality	Primarily *ex-situ* volumetric inspection; acquisition and reconstruction required; component size and material attenuation constrain achievable resolution; acquisition time and cost not consistently reported	Resolution–component-size trade-off; beam-hardening/image artefacts; segmentation and operator dependence
Laser ultrasonics [104]	AlSi10Mg/LMD; buried internal pores/artificial reference defects	Defects of 0.3 mm diameter at 1 mm depth were investigated; lateral-position error <1% and depth-position error <10%; system responsive to defects >0.3 mm diameter and >1 mm depth	Non-contact; pulse-echo configuration; reported receiver maximum detection velocity 5 m/s	Weak echoes and limited SNR for smaller/deeper discontinuities; detection capability geometry- and material-dependent
Optical/deep-learning monitoring [77]	Ceramic VPP; recoating defects	Mean F1 ≈ 0.89; F1 > 0.97 for larger defect classes; processing rate 54.01 frames s^{-1}	*In-situ*, layer-wise, real-time monitoring	Limited to optically accessible process/surface phenomena; performance decreases for small defect targets and depends on training data
3D scanning/LiDAR [126,127,131,132]	External geometry and surface condition; dental-metal and large-scale AM applications	Real-time geometrical inspection demonstrated [132]; quantitative resolution is system/application-specific and is not reported consistently across the reviewed studies	Non-contact; rapid surface acquisition; amenable to automated/*in-situ* integration	No direct access to internal discontinuities; line-of-sight and reflectivity dependence
Acoustic-emission/thermal monitoring [107]	LPBF; process anomalies, build failures, surface and microstructural variation	Quantitative minimum detectable defect size NR in the reviewed study; AE signatures correlated with build failures and quality variation	*In-situ*; high temporal sensitivity; can be combined with IR monitoring	Indirect relationship between signal and final defect morphology; calibration and signal interpretation required

Note: The values reported in Table 15 are representative study-specific capabilities and should not be interpreted as universal detection limits. Spatial resolution, minimum detectable defect size, acquisition rate and measurement uncertainty depend on material attenuation or reflectivity, component geometry, defect morphology and orientation, hardware configuration, acquisition settings and data-processing methodology. Acquisition time and economic cost are reported only where explicitly quantified in the original studies; otherwise, no generic numerical or qualitative ranking is assigned.

4. Discussion

The evidence synthesised in the preceding sections demonstrates that AM defect formation and detection cannot be interpreted independently of process physics, material behaviour, component geometry and inspection capability. The Discussion therefore moves beyond study-by-study description to examine cross-study consensus, apparently contradictory findings, process-specific differences, limitations of the available evidence and their implications for defect-sensitive quality assurance and industrial qualification.

4.1. Critical Synthesis of Consensus, Contradictions and Research Gaps

The reviewed literature reveals a broad consensus that defect formation in AM is governed by the coupled influence of process parameters, feedstock behaviour, thermal history, build orientation, interlayer bonding and post-processing conditions. Across different AM routes, defects such as porosity, cracking, delamination, anisotropy, SR, layer slippage and dimensional deviation are repeatedly associated with localised variations in energy input, insufficient consolidation, unstable material deposition, residual-stress development and non-uniform cooling. A second area of consensus concerns the increasing importance of NDT and advanced inspection methods, particularly computed tomography, optical scanning, thermography and ultrasonic inspection, for improving defect localisation, dimensional verification and confidence in part qualification.

Nevertheless, the literature is less consistent when the relative importance of individual defect drivers is considered. In PBF and DED, defects are frequently attributed to melt-pool instability, insufficient or excessive energy input, spatter, keyholing, rapid solidification and residual-stress accumulation. By contrast, MEX, SHL and MJT are more strongly governed by interlayer bonding quality, deposition stability, droplet coalescence, curing behaviour, sheet alignment and support-removal effects. This indicates that identical defect labels may refer to different physical mechanisms depending on the AM process considered. Porosity, for example, may originate from lack of fusion in PBF, incomplete densification in BJT, inter-bead voids in MEX or unstable melt-pool behaviour in DED.

Viewed through the analytical framework adopted in this review, these differences can be expressed as process-specific causal chains rather than as isolated associations between parameters and defects. In PBF, for example, energy input, hatch spacing, scan strategy and powder-bed condition govern melt-pool geometry, thermal gradients and solidification behaviour; insufficient consolidation promotes lack-of-fusion porosity, whereas excessive local energy input may favour keyholing, while repeated directional heat flow contributes to residual stress, texture and microstructural anisotropy [96,100,101,105]. These resulting material and defect states influence density, tensile behaviour, fatigue resistance, surface condition and dimensional stability and therefore determine whether volumetric inspection, surface metrology or *in-situ* process monitoring is required for subsequent quality assessment [102,103,106,107]. A different causal pathway is evident in MEX. Nozzle temperature, layer height, raster strategy, feed rate and feedstock behaviour determine bead geometry, polymer interdiffusion and interlayer bonding. Inadequate bonding or unstable deposition can consequently generate inter-bead voids, weak interfaces, layer misalignment and poor surface condition, which in turn affect tensile performance and dimensional reliability [68–72]. In this case, layer-wise optical or laser-based monitoring and machine-learning-assisted detection can provide information early enough to support process intervention rather than exclusively post-build acceptance. These contrasting examples demonstrate that the required inspection strategy is a consequence of the underlying process–material–defect pathway and of the performance characteristic that must ultimately be assured.

A similar process dependence is evident in defect detection. CT/XCT is particularly effective for volumetric discontinuities such as internal porosity, lack-of-fusion defects and keyhole pores, whereas optical scanning and surface profilometry are more appropriate for dimensional deviation and SR. Ultrasonic inspection and thermography are especially relevant for delamination, weak bonding and thermal discontinuities, although their reliability depends strongly on material attenuation, geometry, defect orientation, calibration and spatial resolution. Metallography and SEM remain essential for microstructural confirmation, but their destructive and localised nature restricts their use as standalone industrial inspection tools. The evidence therefore supports the use of complementary inspection strategies rather than reliance on a single defect-detection method.

Cross-study comparison further demonstrates that the engineering significance of individual quality phenomena depends strongly on surface state, loading condition and defect morphology. Afroz et al. [50] provide a representative quantitative example for L-PBF AlSi10Mg. The average SR, Ra, decreased from approximately 2.1 μm in the as-built condition to 0.90 μm after machining and approximately 0.75 μm after subsequent polishing. The higher roughness of the as-built specimens was associated with fatigue lives approximately 60–80% lower than those of machined specimens, while under some lower-stress conditions the machined and machined-and-

polished specimens achieved increases in fatigue life of up to approximately 50-fold. However, further reducing Ra from approximately 0.90 to 0.75 μm did not consistently produce an additional improvement in fatigue performance. Once roughness was reduced below approximately 1 μm, pore size, morphology and location became increasingly influential. Within the investigated machined specimens, porosity fractions varied only from approximately 0.05 to 0.25% and average pore sizes from approximately 36 to 46 μm, yet fatigue life did not correlate closely with overall porosity fraction. The evidence instead indicated greater sensitivity to pore size and proximity to the surface. This demonstrates that neither SR nor total porosity can be interpreted as an independent universal predictor of mechanical performance.

The same evidence also demonstrates that AM quality phenomena should not necessarily be interpreted as independent variables. Multiple discontinuities, geometrical deviations and material-state characteristics may coexist and interact in determining the resulting component response. In metallic PBF, for example, SR, near-surface porosity, lack-of-fusion regions, residual stress and directional microstructure may simultaneously influence crack initiation and propagation. Their relative contribution consequently changes with surface condition, post-processing route, build orientation, defect location and applied loading [25,26,48,96]. A surface-connected or near-surface pore may be more detrimental to fatigue performance than a similarly sized internal discontinuity, while machining may suppress the contribution of roughness and expose the influence of subsurface defects.

A comparable interaction occurs in MEX, where inter-bead voids, insufficient interlayer bonding, layer misalignment and surface irregularity may originate from common variations in extrusion temperature, feed rate, raster strategy, layer geometry and cooling history [70,71]. These conditions may act collectively rather than independently to reduce load-transfer efficiency, tensile performance and dimensional reliability. Component integrity should therefore be interpreted in terms of the combined defect population, spatial relationship between discontinuities and local material state, particularly when several quality-limiting phenomena occur within highly stressed regions.

Context dependence is also evident in the interpretation of anisotropy. Dixit et al. [31] examined LPBF 316L using scan-rotation angles of 0°, 45°, 67° and 90° and showed that mechanical anisotropy results from the combined influence of scan rotation, build orientation, dislocation structure and crystallographic texture rather than from scan rotation alone. Importantly, the same study highlights contradictory trends within the published literature. One reported dataset associated a 67° scan rotation with enhanced yield strength, whereas another investigation reported the lowest yield strength at 67° (427 MPa) and the highest at 0° (449 MPa). The latter study also reported tensile strengths of approximately 485 MPa at 67° and 527 MPa at 0°, together with ductilities of approximately 50% and 58%, respectively. Such opposing trends indicate that apparently inconsistent conclusions concerning anisotropy can arise when scan strategy is considered independently of build orientation, microstructural evolution, residual stress and material state. Anisotropy should therefore be interpreted as a coupled process–microstructure–property response rather than as a universally detrimental or single-parameter phenomenon.

Several unresolved challenges remain. First, terminology remains insufficiently standardised, with similar defects described using different expressions across studies, particularly in relation to porosity, lack of fusion, interlayer decohesion, delamination and surface irregularities. Second, inspection workflows are not yet fully harmonised, which limits comparison of detection sensitivity, spatial resolution and diagnostic reliability between studies. Third, although machine-learning-assisted defect recognition and data-driven monitoring are increasingly reported, their broader industrial implementation remains constrained by limited training datasets, inconsistent defect annotation, process-specific calibration requirements and insufficient validation under production-relevant conditions.

The principal research gap therefore lies in the integration of defect formation mechanisms, inspection data and quality-assurance decision-making into coherent frameworks. Future work should move beyond isolated defect detection and towards predictive quality control, combining *in-situ* monitoring, *ex-situ* non-destructive evaluation, standardised defect taxonomies, validated datasets and digital models capable of linking process conditions to defect severity, component performance and acceptance criteria. Such integration is essential for reducing empirical trial-and-error qualification and for improving confidence in the industrial deployment of AMed components.

4.2. Evidence Limitations and Implications for Qualification

Despite the breadth of the reviewed evidence, direct quantitative comparison between studies remains constrained by substantial methodological heterogeneity. Differences in AM process, material system, machine platform, build orientation, process parameters, specimen geometry, post-processing condition, defect terminology and inspection configuration mean that apparently similar defect classes are not necessarily equivalent across

studies. Reported porosity, roughness, anisotropy or dimensional deviation should therefore be interpreted within the corresponding process and measurement context rather than as directly interchangeable quantities.

Inspection evidence is subject to similar limitations. Detection capability depends not only on the inspection technology itself but also on defect size, morphology, orientation and location, together with component geometry, material attenuation, acquisition parameters, spatial resolution, calibration and data-processing procedure. Consequently, the review does not support universal rankings of inspection methods. Instead, the evidence indicates that inspection strategy should be selected according to the expected defect population and the information required for the subsequent quality-assurance decision.

Practical implementation variables are even less consistently reported. Acquisition and reconstruction time, inspection throughput, equipment cost, automation requirements and probability of detection are not documented using common definitions or test conditions across the reviewed literature. Consequently, the present review reports such parameters quantitatively only where they are explicitly available in the source study and does not replace missing values with generic “low”, “medium” or “high” classifications. This lack of harmonised implementation data represents an important evidence gap in itself. Future comparative studies should report, at minimum, material and component geometry, defect morphology and orientation, spatial resolution or voxel size, minimum investigated or detectable defect dimension, measurement uncertainty and repeatability, acquisition and processing time, *in-situ* or *ex-situ* applicability and an explicit basis for economic cost. Such reporting would enable inspection performance to be compared on a traceable engineering basis rather than through technology-level generalisations.

For qualification-oriented NDT, minimum detectable defect size, nominal spatial resolution and probability of detection (POD) should not be treated as equivalent quantities, as specified within ASTM E2862-23, Standard Practice for Probability of Detection Analysis for Hit/Miss Data. A reported minimum detectable feature represents the capability demonstrated under a specific experimental configuration, whereas POD expresses the statistical probability that a discontinuity of a given size will be detected under defined examination conditions. Similarly, repeatability characterises variation under nominally unchanged measurement conditions, while measurement uncertainty describes the range within which the measurand may reasonably lie. Consequently, a single voxel size, spatial resolution or experimentally detected defect dimension cannot by itself establish inspection reliability. Where the reviewed studies do not provide repeated trials or statistically defined POD data, the present review reports only the demonstrated study-specific capability and does not infer a POD relationship.

These limitations are particularly important when inspection results are translated into industrial acceptance criteria. Defect presence alone does not determine component fitness for service. The relevant engineering question is whether the observed condition compromises the required dimensional, mechanical or functional performance under the intended loading and service environment. Qualification should therefore combine defect characterisation with process history, material condition, component geometry and application-specific performance requirements. Where formal acceptance criteria are available, these should be established through the applicable product, material, process or sector-specific qualification framework rather than inferred from generic defect-severity categories.

The principal evidence gap is consequently not the absence of defect-detection techniques, but the limited availability of harmonised relationships linking process conditions, quantitatively characterised defect populations, inspection capability and service-relevant performance. Greater consistency in defect terminology, reporting practice, measurement uncertainty, detection limits and validation methodology is required before robust cross-process quantitative acceptance criteria can be established. Future work should therefore prioritise comparable datasets and qualification-oriented studies capable of connecting process → material response → defect → performance → detectability → acceptance within a traceable engineering framework.

4.3. Emerging Intelligent and Closed-Loop Quality Assurance

The reviewed evidence indicates that AM quality assurance is progressively moving from post-process defect identification towards systems in which sensing, data interpretation and process intervention are connected within a closed-loop architecture. AI-assisted monitoring already demonstrates this transition at process level. De La Rosa et al. [69], for example, reported a CNN-based material-extrusion monitoring framework with 92.86% validation accuracy in which detection of stringing, over-extrusion, under-extrusion and weak infill was coupled with dynamic G-code modification. Özel et al. [72] further incorporated process knowledge into physics-informed machine-learning-based defect identification, illustrating a pathway towards models whose predictions are constrained by manufacturing physics rather than by statistical correlation alone. In VPP, the real-time recoating-defect approach of

Jia et al. [77] achieved an overall F1 score of approximately 0.89 at 54.01 frames s^{-1}, further demonstrating the potential for layer-wise quality information to support intervention before completion of the build.

Multimodal sensing and ultrasonic inspection provide complementary information within this architecture. Acoustic-emission and infrared signals can provide temporally resolved evidence of process anomalies [107], whereas laser ultrasonics enables non-contact interrogation of buried internal discontinuities [104] and immersion ultrasonics has been correlated with XCT-derived porosity distributions in binder-jetted components [121]. These methods therefore address different levels of the process–quality chain and should be considered complementary rather than interchangeable. Combining thermal, optical, acoustic and volumetric information through sensor fusion can improve defect traceability by linking transient process signatures to the final defect state, although calibration, synchronisation, uncertainty propagation and transferability across machines and materials remain important barriers.

DT provide a potential architecture for maintaining this relationship between process state, predicted material response, *in-situ* sensing and *ex-situ* inspection over the component lifecycle. Recent LPBF research has demonstrated DT concepts specifically aimed at rapid *in-situ* qualification of part quality, while broader laser-AM reviews identify multimodal monitoring, machine-learning-assisted interpretation and closed-loop defect remediation as key enabling technologies for autonomous, zero-defect manufacturing [127]. In such a workflow, inspection evidence can be used at three levels: during manufacture, to support anomaly detection and parameter correction; after manufacture, to validate the predicted defect state and update process–quality models; and during qualification, to relate the measured condition to application-specific acceptance criteria. Autonomous quality assurance therefore requires not only accurate sensing and classification, but also traceable uncertainty, validated decision rules and a demonstrable connection between corrective action and final component performance.

Figure 10 consolidates the relationships developed throughout the review into a complete AM quality-assurance workflow. The framework begins with the manufacturing process, feedstock and operating parameters and follows their influence through material and microstructural response, defect or quality manifestation and component performance. *In-situ* monitoring and *ex-situ* inspection then provide complementary evidence for defect characterisation and uncertainty-aware decision-making. Depending on the resulting fitness-for-purpose assessment, this evidence may support component acceptance, further inspection, post-processing, rejection or feedback to process parameters. Data-driven classification, sensor fusion, physics-informed modelling and DT concepts act across these stages by connecting process signatures with the measured and predicted state of the component.

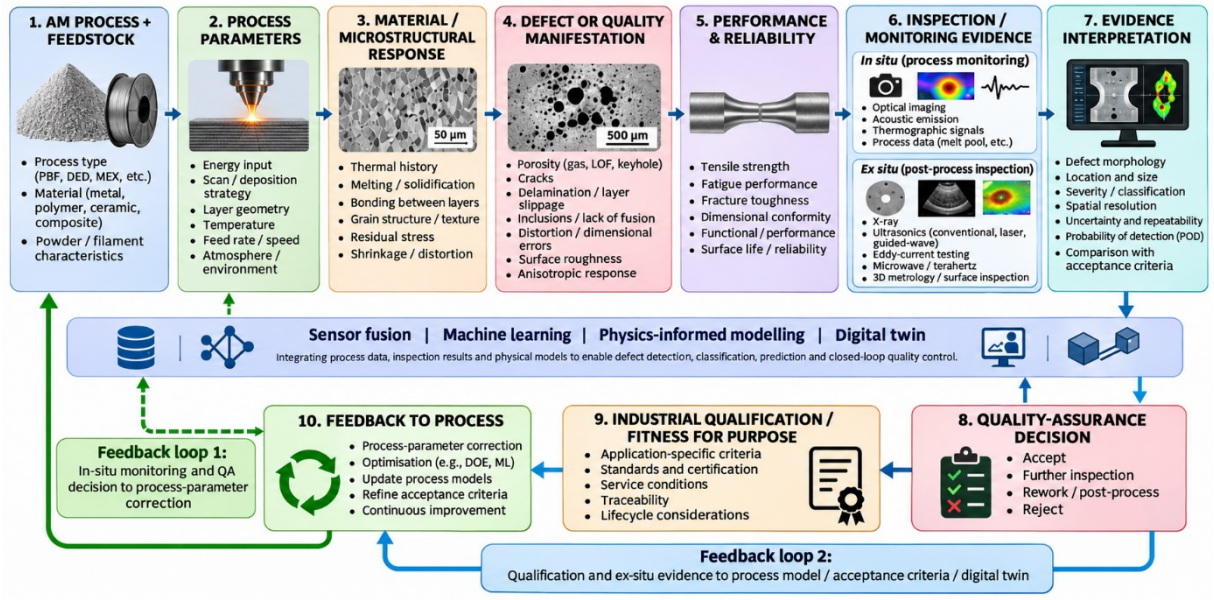


Figure 10. Integrated quality-assurance workflow for AM linking process and feedstock conditions, manufacturing parameters, material and microstructural response, defect or quality manifestation, component performance, inspection evidence, quality-assurance decision-making, process feedback and industrial qualification. *In-situ* and *ex-situ* measurements provide complementary evidence, while sensor fusion, machine learning, physics-informed modelling and DT concepts support interpretation, feedback control and qualification.

5. Conclusions

This systematic review examined defect formation, performance consequences, detection and quality assurance across the principal AM process categories using representative evidence from metallic, polymeric, ceramic and composite material systems. The review was intentionally structured as a cross-process and cross-material synthesis rather than an exhaustive material-specific survey. Material systems were therefore treated as contextual variables within the process–material–defect relationship, enabling common and process-specific mechanisms to be compared without implying comprehensive coverage of every possible AM material–defect combination.

Within this defined scope, the synthesis demonstrates that defects in AM should not be interpreted as isolated imperfections, but as outcomes of interacting process, material, geometry and thermal-history variables. Their physical origin, morphology, performance consequence and detectability can differ substantially between AM routes even where similar defect terminology is used. The resulting analytical framework therefore links process category → material response → defect-generation mechanism → defect manifestation → performance consequence → detectability and quality-assurance response. Across the reviewed evidence, porosity, lack of fusion, cracking and delamination emerge as recurrent discrete manufacturing defects; dimensional deviation and layer misalignment as geometrical quality deviations; SR as a process-sensitive surface attribute; and residual stress, microstructural heterogeneity and anisotropic behaviour as material-state or directional-response phenomena. Their engineering significance remains dependent on process route, material system, component geometry and application requirements.

From an industrial perspective, three recommendations can be drawn. First, AM qualification should adopt process-, material- and application-specific defect-control strategies rather than generic acceptance criteria. Defect origin, morphology, detectability and engineering significance differ across MEX, MJT, SHL, PBF, DED, VPP and BJT and are further conditioned by material system, component geometry and service requirements. Second, quality assurance should combine complementary inspection methods. CT/XCT is particularly relevant for volumetric defects, optical scanning and profilometry for surface and dimensional deviations, and ultrasonic testing or thermography for delamination, weak bonding and thermal discontinuities. Third, defect assessment should be linked to performance consequences, since industrial relevance depends not only on detectability, but also on defect location, recurrence, severity, loading condition and application-specific risk.

Future research should prioritise the development of standardised AM defect taxonomies, harmonised inspection protocols and validated severity-based acceptance criteria. Greater attention is also required to the quantitative relationship between process parameters, defect morphology and mechanical performance, particularly under fatigue, thermal cycling and service-representative loading. In addition, larger and better-annotated datasets are needed to support reliable machine-learning-assisted defect recognition, especially across different machines, materials, build strategies and inspection configurations. Further work should also address the integration of surface metrology, volumetric inspection and process monitoring into unified qualification workflows.

Emerging technological opportunities are centred on predictive quality assurance. The most promising developments include *in-situ* monitoring, DT-assisted process control, automated defect classification, hybrid NDT workflows, high-resolution three-dimensional surface metrology and data-driven links between process signatures and final component integrity. These approaches may reduce dependence on post-build inspection alone and support earlier intervention during manufacturing. Overall, the transition from defect detection to defect prediction represents a central requirement for the broader industrial qualification and reliable deployment of AMed components in safety-critical and high-performance applications.

6. Research Agenda and Future Directions

Future research on defects in AMed parts should move beyond descriptive defect cataloguing and towards a more integrated understanding of the process–defect–property relationship. Although substantial progress has been made in identifying recurrent defects and defect-sensitive quality phenomena, including porosity, cracking, delamination, dimensional deviation, SR and anisotropic response, the field still lacks sufficiently generalisable frameworks capable of linking defect formation mechanisms to specific combinations of process parameters, feedstock characteristics, thermal histories and geometric constraints. Greater emphasis should therefore be placed on cross-process comparative studies that clarify which defect mechanisms are process-specific and which reflect broader material or interfacial phenomena common to layer-wise manufacturing.

A second priority concerns the development of more robust, multimodal and industrially deployable inspection strategies. Current research demonstrates the value of non-destructive evaluation, process monitoring and advanced imaging techniques; however, these approaches are still too often investigated in isolation. Future work should focus on the integration of *in-situ* sensing, *ex-situ* inspection and data-fusion methodologies capable

of combining thermal, optical, geometric and volumetric information within a unified diagnostic framework. In particular, the coupling of process-monitoring signals with post-process inspection data could substantially improve defect traceability, enhance interpretative confidence and support earlier intervention during manufacture.

Further progress will also depend upon improved standardisation in defect terminology, reporting practice and validation methodology. The literature continues to exhibit considerable inconsistency in the way similar defects are defined, measured and classified, which hinders rigorous comparison across studies and limits the reproducibility of conclusions. Future investigations should therefore prioritise the establishment of harmonised defect taxonomies, standardised reporting descriptors and benchmark protocols for inspection performance, including sensitivity, resolution, uncertainty and defect-detection limits. Such developments would provide a stronger evidential basis for qualification procedures and facilitate more meaningful comparison between AM routes, material systems and monitoring technologies.

Another promising direction lies in the use of intelligent and physics-informed analytical tools. Machine learning, anomaly detection and data-driven quality assessment have shown considerable promise, yet their broader application remains constrained by limited dataset quality, insufficient interpretability and poor transferability across machines and materials. Future research should therefore seek to combine statistical learning with mechanistic modelling, thereby enabling predictive frameworks that are not only computationally efficient but also physically credible. The development of defect-aware DT may prove especially valuable in this regard, as they could support real-time quality prediction, adaptive parameter control and lifecycle-informed qualification of critical components.

Finally, future work should place greater emphasis on industrial qualification and economic feasibility. For AM to achieve broader deployment in safety-critical and high-value applications, defect detection must be embedded within coherent quality-assurance architectures rather than treated as a stand-alone inspection task. This will require scalable workflows capable of balancing diagnostic performance, cost, throughput and implementation complexity. Accordingly, the next stage of research should aim to deliver integrated quality frameworks in which process optimisation, defect monitoring, inspection, validation and acceptance criteria are treated as interdependent elements of a unified manufacturing strategy. In this way, defect analysis will evolve from a predominantly diagnostic function into a predictive and decision-support capability central to the reliable industrialisation of AM.

The research needs identified through the systematic synthesis can therefore be consolidated into five interconnected priorities. Rather than representing independent research topics, these priorities form a progression from improved understanding of defect causation to reliable detection, prediction and ultimately qualification. Table 16 summarises the resulting research agenda and the principal scientific outcomes required to advance defect-sensitive quality assurance in AM.

Collectively, these priorities define a transition from defect identification towards predictive and qualification-oriented quality assurance. Progress will require not only improved sensors or algorithms, but experimentally validated causal links connecting process state, material response, measurable defect morphology, component performance and inspection uncertainty. Establishing these links represents a principal scientific challenge for the next generation of AM quality-assurance research.

Table 16. Research agenda for defect-sensitive quality assurance in AM.

Research Priority	Current Limitation	Required Research Direction	Expected Scientific/Industrial Outcome
Cross-process causal mapping	Defect labels are frequently compared without sufficient consideration of process physics and material response	Establish quantitative relationships among process parameters, material behaviour, thermal history, geometry and defect morphology across AM routes	Transferable process–material–defect models and clearer distinction between common and process-specific mechanisms
Multimodal inspection and sensor fusion	*In-situ* monitoring and *ex-situ* NDT are frequently investigated independently	Integrate thermal, optical, acoustic, dimensional and volumetric information with traceable spatial and temporal correlation	Improved defect traceability and higher confidence in diagnosis
Standardisation and benchmarking	Terminology, defect descriptors, resolution, uncertainty and validation procedures vary substantially between studies	Develop harmonised taxonomies, reference artefacts, benchmark datasets and reporting protocols	Improved reproducibility and meaningful comparison between inspection technologies
Physics-informed prediction	Data-driven models often exhibit limited interpretability and poor transferability across machines and materials	Combine machine learning with process physics, uncertainty quantification and defect-aware DT	More generalisable predictive quality models and adaptive process control
Qualification and fitness-for-purpose	Defect detection is not consistently connected to performance or application-specific acceptance criteria	Link quantified defect populations and inspection capability to fatigue, fracture, dimensional and functional performance	Evidence-based acceptance criteria and integrated industrial qualification workflows

Author Contributions

A.G.P. and I.M.P.: conceptualization, formal analysis, supervision, validation; A.F.V.P.: methodology, investigation, writing—original draft preparation, writing—review and editing; N.P.V.S.: methodology, data curation, writing—review and editing; R.D.F.S.C.: methodology, validation, data curation, visualization; M.L.S.B.: validation, data curation; A.H.M.R. and J.P.C.G.: writing—original draft preparation. All authors have read and agreed to the published version of the manuscript.

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No new data was created.

Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

During the preparation of this work, the authors used Grammarly Premium v6.8.263 to verify and improve the British (UK English) language employed. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article

Appendix A

PRISMA 2020 Flow Diagram for New Systematic Reviews, Which Included Searches of Databases and Registers

This section presents the PRISMA 2020 flow diagram used to document the identification, screening, eligibility assessment and final inclusion of studies considered in the present systematic review. The diagram provides a transparent representation of the literature-selection pathway and supports methodological traceability, consistency and reproducibility in accordance with the PRISMA 2020 framework.

The systematic search strategy was specifically designed to identify peer-reviewed literature published between 2010 and 2025 concerning defects in AMed parts, with particular emphasis on defect classification, defect formation mechanisms, defect-detection methods, non-destructive evaluation, process monitoring, and the broader implications of these approaches for part quality, dimensional fidelity, structural integrity, process reliability and component performance. To ensure thematic precision, the search incorporated predefined keyword groups related to AM technologies, defect-related phenomena, inspection and monitoring approaches, and quality-assessment methodologies, combined through Boolean logic and applied to the title, abstract and keyword fields of the selected databases. The complete numerical progression of the study-selection procedure is presented in Figure A1. The flow diagram reports the number of records initially identified through CrossRef, the number removed during bibliographic deduplication, the records retained for title and abstract screening, the publications subjected to full-text eligibility assessment, the reasons for exclusion at the full-text stage and the final number of studies included in the systematic-review corpus.

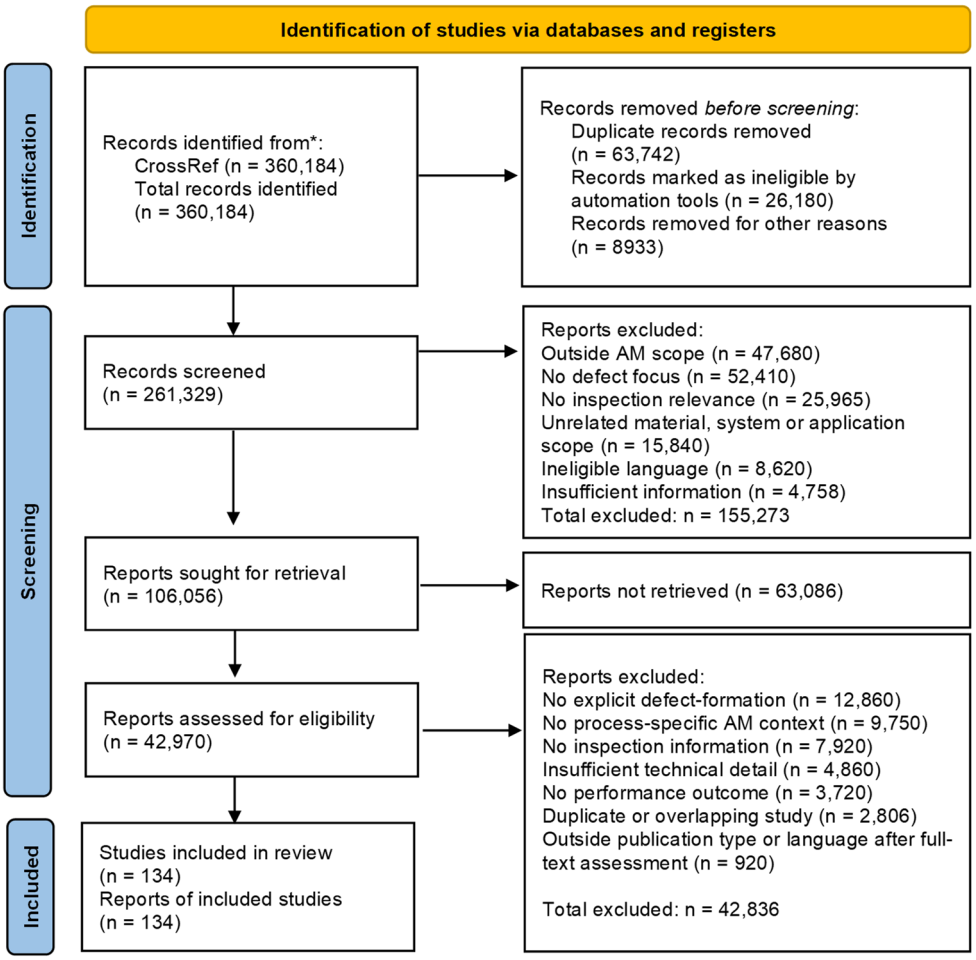


Figure A1. PRISMA 2020 flowchart for the systematic review of defects in AMed parts, with particular emphasis on defect classification, defect formation mechanisms, defect-detection methods, non-destructive evaluation and process-monitoring approaches.

Appendix B

List of Abbreviations

Table A1 compiles the abbreviations used throughout this study, together with their corresponding definitions, to ensure terminological consistency and to facilitate interpretation of the defect typologies, AM processes, inspection methods, quality-related descriptors and analytical terms discussed in the manuscript. This appendix is intended to serve as a concise reference for readers and reviewers.

Table A1. List of abbreviations.

Abbreviation	Meaning
AM	Additive Manufacturing
NDT	Non-Destructive Testing
SEM	Scanning electron microscopy
AFM	Atomic force microscopy
CAD	Computer Aided Design
CT	Computed tomography
FDM	Fused Deposition Modelling
MEX	Material Extrusion
VPP	Vat photopolymerization
MJT	Material Jetting
SHL	Sheet Lamination
PBF	Powder Bed Fusion
DED	Directed Energy Deposition
BJT	Binder Jetting

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