



A Comprehensive Review of In-Situ Monitoring and Post-Process Defect Detection in Additive Manufacturing

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Abstract

Additive manufacturing (AM) technology has revolutionised the creation of metal and polymer parts within aerospace, biomedical, automotive, and energy industries; however, susceptibility to defects has hindered certification and implementation within industry. This study provides a critical review of in-situ monitoring and post-processing defect detection methods within AM. In contrast to the existing review literature which solely discusses techniques by domestic, this study aims to add value by providing a Technology Readiness Level (TRL) rating (1-9) of 12 techniques, a unique defect-technique mapping approach with detectability ratings (1-5), and an innovative decision framework with an ability to minimise the amount of post-processing inspections by up to 40-60%. The defects, including porosity, lack of fusion, cracking, delamination, and distortion, are classified according to powder bed fusion, directed energy deposition, and extrusion-based methods of additive manufacturing. Some of the main gaps revealed in this review include a lack of validated fusion models, certification pathways allowing for the use of in-situ data, and low industry TRL (3-4) for combined multisensor monitoring systems. Future research areas include benchmarking data sets, standards within ASTM F42/ISO/ASTM 52900, and closed-loop control systems.

Keywords: Additive manufacturing, In-situ monitoring, Post-process inspection, Defect detection, Non-destructive testing, Quality assurance, Process control.

1.0 Introduction

Additive manufacturing, also known as three-dimensional printing, has revolutionized the design and manufacturing of metallic and polymeric components, allowing the fabrication of parts directly from digital data in a layer-wise manner [1]. While initially used as a tool for rapid prototyping, additive manufacturing technology has now emerged as a viable production technology for the fabrication of complex components in mission-critical industries such as aerospace, biomedical, automotive, and energy sectors [2]. The layer-wise manufacturing approach allows the fabrication of geometrical features that are difficult, if not impossible, to achieve using traditional manufacturing approaches, allowing for lightweight design and reduced material waste [3]. However, unlike traditional subtractive manufacturing, in which the quality of the manufactured components is ensured through established standards, the process physics of additive manufacturing are highly prone to defect issues, which can affect the performance of the components [4]. The defect issues in additive manufacturing, especially in the case of mission-critical industries, have led to a slowdown in the acceptance of additive manufacturing as a certified manufacturing technology [5,6]. As emphasised in the article by Dey et al. [7], with the advent of additive manufacturing in mission-critical industries, the need for internal consistency in the manufactured components is of utmost importance.

The types of defect that are present in Additive manufacturing are complex and varied in nature. Some of the most commonly observed types of defect in AM include porosity, lack of fusion, cracks, delamination, and residual distortion [8,9]. These types of defects may be internal in nature or may be present in areas that cannot be accessed without sectioning off the manufactured component. Though destructive testing may be used to detect such types of internal defects in AM, it cannot be practically implemented in AM due to the unique design of each manufactured component and because destructive testing would essentially destroy a valuable component, thereby negating its use and value [10]. Moreover, due to the geometrical complexity that is often present in Additive manufacturing-built components, sampling may not be representative in nature and therefore cannot be effectively addressed by quality assurance methods [11,12]. In-situ monitoring has therefore emerged as a significant area of research and application in addressing issues in AM quality control. In-situ monitoring essentially entails the use and application of sensors that are incorporated into or around the AM process in order to monitor process

signatures such as optical emissions, thermal profiles, and acoustic emissions during deposition [10]. A significant differentiation must be made between monitoring and defect detection in AM quality control. Essentially, monitoring entails a continuous process in which data may be used as a proxy to assess process status, while defect detection essentially entails determining whether a specific type of anomaly has occurred in a particular process [14].

However, despite its potential, in-situ monitoring is not considered adequate by itself as a quality assurance tool, especially because many monitoring tools are not sufficiently sensitive to detect defects that are deeply embedded or located beneath the surface, while issues of signal noise, data volume, and complexity of data interpretation pose significant challenges to implementation [15]. Monitoring involves the continuous capture of process signals, such as temperature and optical signals, in real time in order to evaluate process stability. The term detection refers to the recognition of an anomaly related to a particular type of defect [14]. Thus, post-process inspection is required to ensure part quality, where non-destructive testing techniques such as X-ray computed tomography, ultrasonic testing, and thermographic testing have been effectively employed [16]. Various reviews have already been conducted to understand the concept of defect monitoring and inspection in additive manufacturing, though there is still much to explore. Most reviews have focused on a particular sensing method, such as digital image correlation-based deformation measurement techniques [13], acoustic emission-based metal additive manufacturing process monitoring [17], while others have focused on condition monitoring techniques, though not sufficiently assessing how these techniques can be effectively integrated, their level of maturity, and how in-situ monitoring can effectively link with post-process quality assessment [18,19]. Additionally, there is also a lack of progress in the literature regarding standardisation, certification gaps, and the conversion of monitoring data into reliable qualification proof.

Several recent studies have provided a comprehensive overview of the in-situ process control methods [10,13,16] as well as the post-process inspection techniques [15,19]. However, upon careful consideration, numerous contradictions arise, which make generalizations impossible. For instance, the accuracy of optical process control in terms of detection of porosity varies between 45% and 92% in five separate studies [14,17,27,42,44]; there is no standard approach to calibrating such equipment. Moreover, acoustic emission thresholds for crack detection vary tenfold among different PBF processes [17,44]; only 30% of X-ray CT studies include all the necessary parameters of analysis [19,43]. Also, there are no clear pathways to certification. As of 2024, only 17 additively manufactured medical devices have been approved by the FDA [37], while the FAA has certified fewer than 10 AM flight-critical parts [38] despite thousands of papers in the literature. While the ASTM F42 committee has released standards on data formats (F3490-21), there is no standard for utilizing the in-situ data for certification purposes [6,45]. In a survey conducted in 2023 among 150 industrial users of AM technology, 78% indicated "no clear pathway to certification" as the main hindrance to implementing in-situ monitoring during production [10]. As well, only 12% of published peer-reviewed journals on in-situ testing have incorporated any form of validation that correlates their sensors' outputs with mechanical performance, such as fatigue life, tensile strength after processing [16,19]. Out of these, only three articles [8,20,42] have correlated their in-situ signatures with defect geometry measured by X-ray CT.

This study reviews recent progress in AM in situ sensing and post-process inspection for defects. Unlike conventional literature, which only describes sensing techniques, their benefits, drawbacks, and technological readiness level (TRL) were discussed. Three critical research gaps are identified, which presently hinder the development of certifiable AM quality assurance systems, such as a lack of any framework that correlates in-situ signatures to defect metrics after processing, a lack of certification paths that consider in-situ data to be an acceptable basis for certification (ASTM, FAA, FDA, ISO), and low TRL for data fusion technology suitable for manufacturing processes.

This study proposes solutions to these challenges by comparing different sensing technologies based on TRL and detectability scores, developing a monitoring-inspection approach, and outlining future research priorities.

2.0 Defects in Additive Manufacturing: Origins, Classification, and Implications

Basic defects in additive manufacturing, their origins, classification, and implications are discussed in this section.

2.1 Fundamental Defect Types in Additive Manufacturing

Defects in additively made components can take several forms, each with its own causes and implications for part performance. Porosity, absence of fusion, cracking, residual stress accumulation, delamination, surface roughness, and microstructural inhomogeneity are among the most common defects [8,9]. Understanding these fault categories is essential for developing monitoring techniques and inspection protocols in additive manufacturing, as seen in Figures 1 and 2. Porosity results from entrapment of gases either during layer bonding or due to poor melting conditions, leading to internal cavities, which could be spherical shaped (gas porosity, diameters of 10-50 μm) or irregular (keyhole porosity, diameters of 50-200+ μm) [20]. On a quantitative basis,

porosity even as low as 0.5-1% can cause a reduction in fatigue life of Ti-6Al-4V and Inconel 718 materials by 50-80% [8]. Pores greater than 100 μm diameter initiate major cracks, reducing fatigue strength from 500 MPa for fully dense materials to 250 MPa at 1% porosity. Gas porosity results from trapped inert gas or vapors, while keyhole porosity results from high volumetric energy density (>200 J/mm³), leading to deep vapor cavities collapsing during solidification [20].

Lack of fusion defects involve the failure of two or more layers to fuse correctly, leading to poor interfaces between layers. This type of defect is characterized by unmelted powder particles and poor metallurgical bonding. These defects are usually due to insufficient energy input, hatch spacing, and scanning speed [21]. Cracking, including hot cracking and solidification cracking, involves the formation of fissures due to temperature gradients and stresses exceeding the material's strength during the process. These defects compromise the structure's integrity and may propagate under mechanical loading [22]. Delamination involves the separation of layers due to poor bonding between them, especially in regions with high residual stress concentrations [23]. Surface roughness may compromise the structure's accuracy, as well as its appearance and performance, especially when the structure should have specific tribological and hydrodynamic characteristics [24]. Microstructural defects, such as irregular grain development, may compromise the structure's mechanical properties, leading to poor performance [25]. This type of defect does not involve the formation of defects such as voids and cracks, but compromises the structure's integrity by affecting the mechanical properties of the structure in different regions.

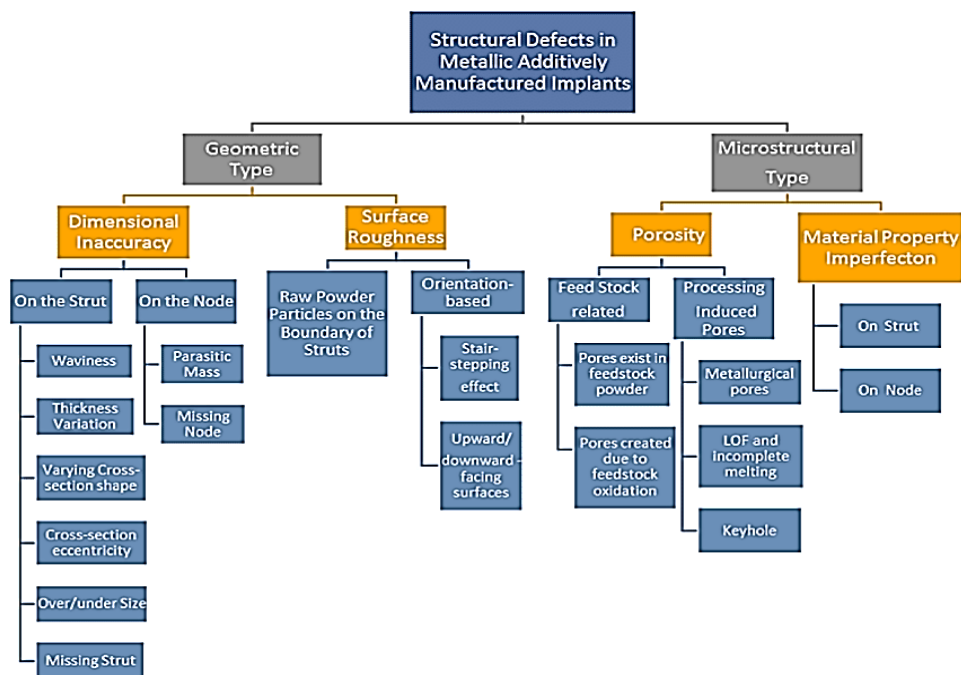


Figure 1: Classification of Different Defect Types Commonly Occurring in Additive Manufacturing [26]

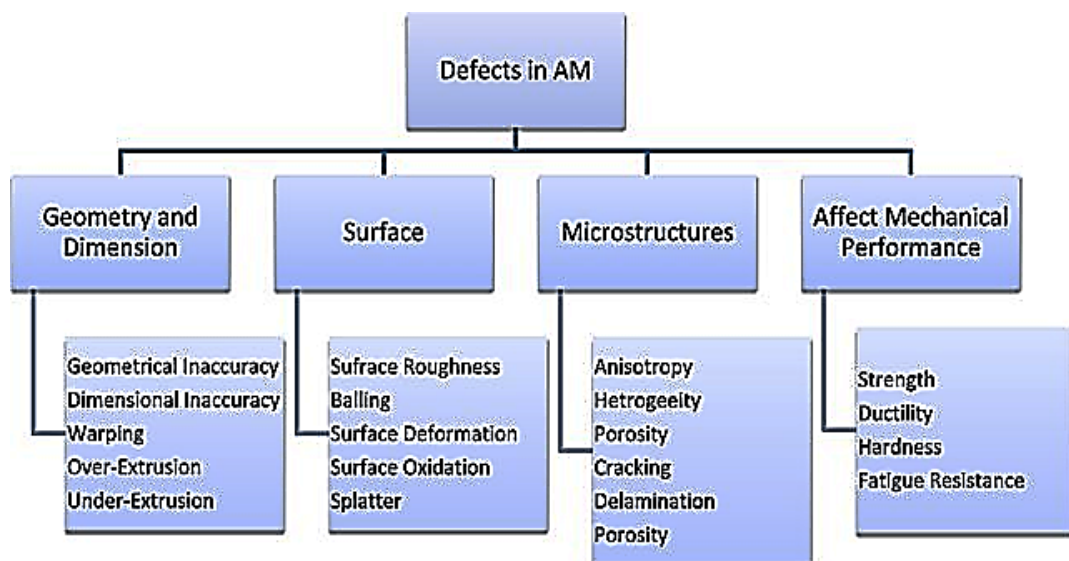


Figure 2: Defects in Additively Manufactured Components [27]

2.2 Process-Parameter-Defect Relationships Impact on Structural Integrity

Figure 3 illustrates that defect and their severity are dependent on process parameters and material properties. The laser power, scanning speed, hatch spacing, layer thickness, and powder properties all have an impact on melt pool stability and consolidation during powder bed fusion and directed energy deposition processes [10,16]. Low laser power may cause fusion defects, whereas high laser power may cause keyhole-related defects and spatter defects [20]. Rapid cooling rates, common in metal additive manufacturing, cause high residual stresses, making distortion and cracking more probable [8]. In polymer additive manufacturing using an extrusion-based process, the temperature of the nozzle, feed rate, and print speed affect adhesion and accuracy. Incorrect parameters cause delamination and voids [28]. The viscosity of the polymer melt, which is highly dependent on temperature, determines how easily other filaments melt and bond. Low temperature or high speeds cause insufficient bonding, resulting in voids that compromise structural integrity.

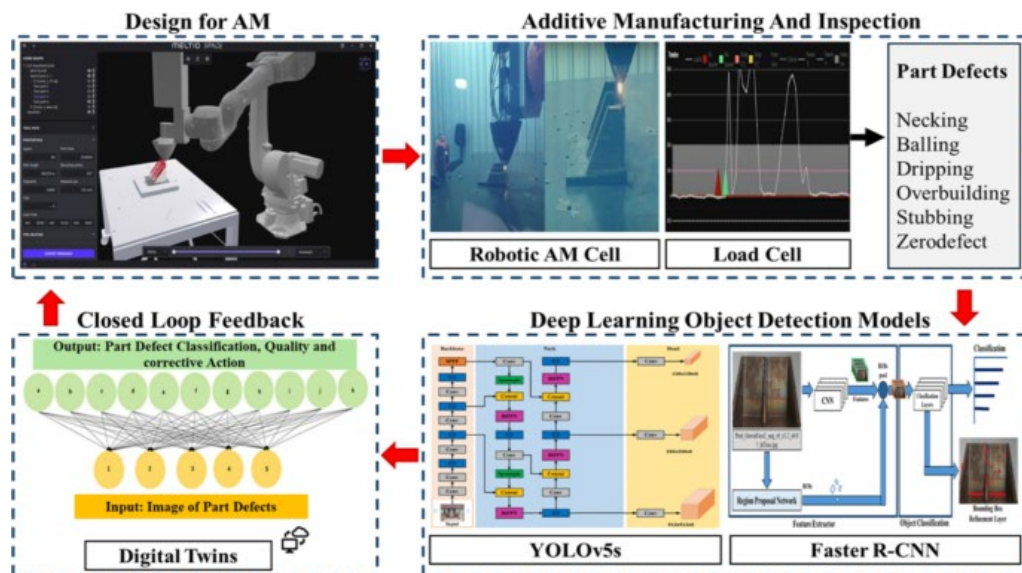


Figure 3: Classification Framework that Categorizes Defects in Additive Manufacturing [29]

According to Chacón *et al.* [21], layer height and raster orientation were identified as two of the most critical parameters affecting inter-layer fusion and fibre orientation. Increasing layer height could cause insufficient compaction and bonding between individual layers, and incorrect raster orientation could cause sub-optimal fibre orientation with respect to the loading direction, hence reducing tensile and flexural strength. The parameters affecting defects during fibre-reinforced polymer composite fabrication include fiber tension, matrix flow rate, and fiber impregnation, among others, as noted by [30]. Improperly selected parameters could cause partial impregnation of fibres, air pockets, and bonding between individual layers, hence affecting tensile strength, flexural modulus, and impact resistance.

2.3 Impact on Mechanical and Functional Performance

Defects in components fabricated via additive manufacturing techniques play a significant role in affecting the mechanical and functional properties of the components, particularly in terms of load-bearing capacity, fatigue resistance, and fracture toughness. Internal porosities and unfused defects were observed as stress concentrators, leading to crack propagation under cyclic loading conditions [9]. Cracks and delamination in the structure are related to defects in continuity, while microstructural inhomogeneity arises due to anisotropic properties, which are different from those required in the design [31]. Surface roughness affects dimensional accuracy, tribological, and fluid properties, as well as mating surface fit [8,15]. Thus, defects in components fabricated via additive manufacturing techniques play a significant role in affecting the mechanical properties, particularly in terms of load-bearing capacity, fatigue resistance, and fracture toughness, and thus, defects must be recognised in the components fabricated via these techniques. Figure 4 depicts defects in components fabricated via additive manufacturing techniques.

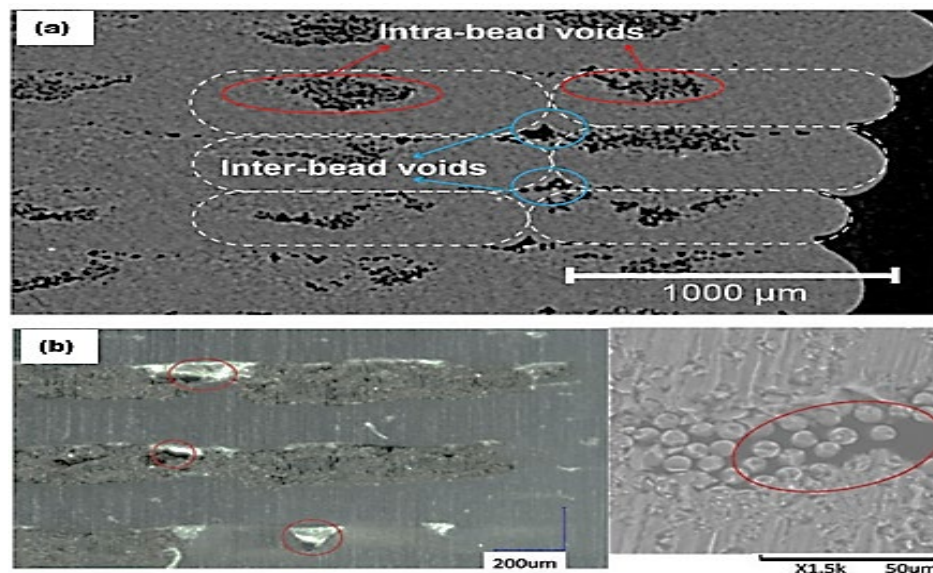


Figure 4: Defects in Additively Manufactured Components: (a) Intra-Bead and Inter-Bead Voids, (b) Carbon Fiber Bundles Under Optical and Electron Microscopy [32, 33]

2.4 Surface Textures: Origins, Characterization, and Functional Implications

The textures that are created on the surfaces of the components that are manufactured through additive manufacturing are quite distinct from those that are created through traditional manufacturing techniques. The stair-stepping effect, the presence of unfused powder particles, and the abnormalities that occur during the scan track are some of the characteristics that dictate the roughness of the surfaces that are created through additive manufacturing [24]. There are several sources of surface textures in additive manufacturing techniques. The sources of surface textures in powder-based additive manufacturing techniques include the sticking of unfused or partially fused powder particles to the surfaces, which creates rough surfaces depending on the size of the powder particles. The periodic textures that are created through extrusion-based additive manufacturing techniques are attributed to the diameter of the filament that is deposited and the spacing that occurs between the roadways. The surfaces in all additive manufacturing techniques are affected by the direction in which they are facing, with the downward-facing surfaces having more roughness than the surfaces that face upwards.

Surface roughness is known not only to affect the surface texture and appearance but also other significant properties. In mechanical assemblies, surface roughness is known to affect the surface friction and wear, which may be undesirable. Surface texture is critical in parts that handle fluids, where it may affect fluid resistance and the possibility of fouling and biofilm formation [8]. Surface defects, perhaps most critical in structural parts, are known to cause stress concentrations, leading to fatigue failure. Surface texture and fatigue performance are closely related in that surface roughness is known to reduce fatigue life. Rough surfaces have shorter fatigue life since surface valleys are preferred sites where fatigue failure is likely to start. Surface roughness is critical in ensuring the performance of parts made using additive manufacturing in safety-critical applications. Figure 5 shows surface textures created using different additive manufacturing techniques, such as FDM, SLA, and SLS, and their distinguishing features and roughness scales.

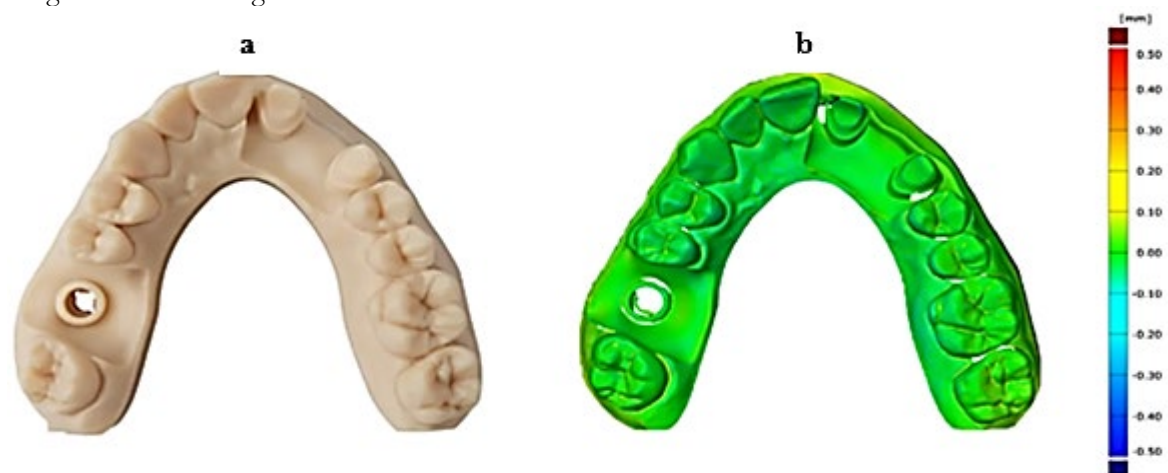


Figure 5: Comparison of Surface Textures Produced by (a) FDM and (b) SLA Technologies, Showing Characteristic Features and Roughness Scales [34]

2.5 Strategies for Mitigating Defect Formation

Effective defect prevention requires sophisticated techniques that take into account the associated role of printing parameters, materials, and monitoring. Figure 6 illustrates various techniques developed as a result of a recent study. Parameter optimisation is the key to defect mitigation techniques. Manufacturers can design reliable build recipes for various materials and geometries by thoroughly investigating processing windows and identifying various parameter combinations that reduce defect formation [28]. It is possible to achieve this via design of experiment techniques, as well as machine learning optimisation. In-situ adaptive control is a more advanced strategy in which monitoring data is used to alter parameters in real time. When sensors detect situations indicative of emerging problems, such as aberrant melt pool temperatures or uneven track geometry, control algorithms change parameters to restore steady processing [16]. This technique necessitates reliable sensing, fast data processing, and well-defined control principles.

Optimising toolpaths can assist in minimising defect formation by controlling the thermal history and residual stress formation through optimal deposition strategies. Various scanning strategies, such as island scanning, interlayer rotation, and contour-first scanning, have been found to reduce distortion and crack defects in metal-based additive manufacturing processes [20]. Post-processing techniques such as hot isostatic pressing, heat treatment, and surface finishing can assist in mitigating or reducing the effects of defects that already exist. Hot isostatic pressing eliminates porosity by subjecting the part to heat and pressure, while surface finishing techniques such as machining, polishing, or blasting can reduce surface roughness and eliminate defects on the surface [35].

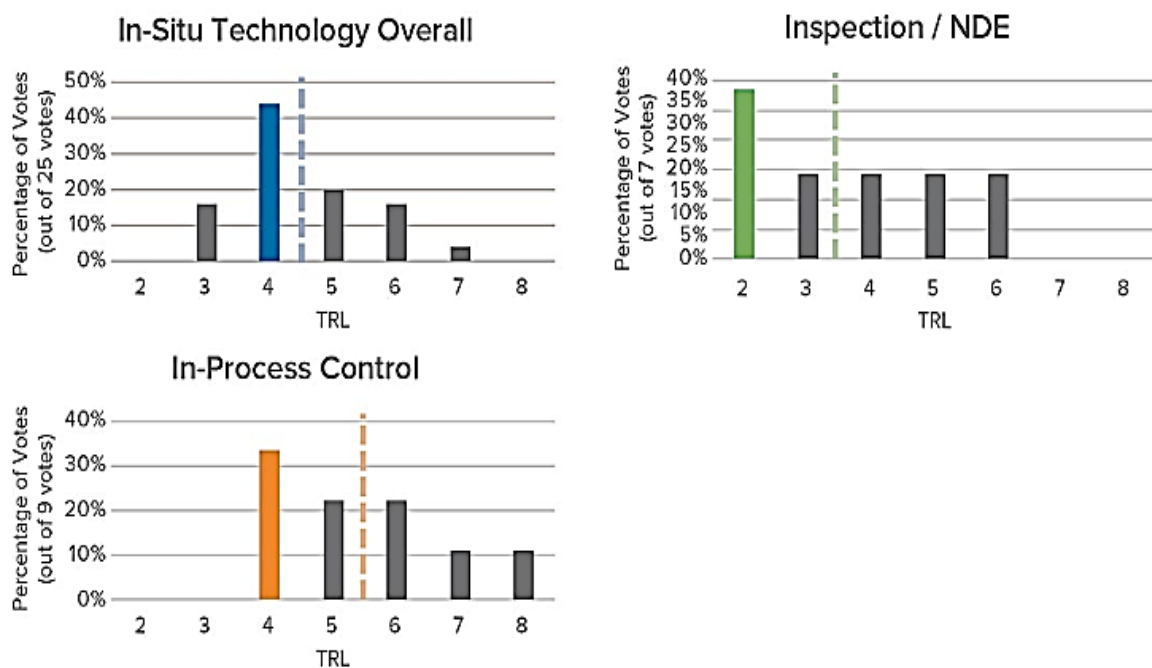


Figure 6: In-situ monitoring (ISM) [12]

2.6 Synthesis: Linking Process Physics to Defects

For all additive manufacturing (AM) processes, defects are the direct result of the underlying physics of the process, including temperature gradients, material flow, energy absorption, and chemical reactions that interact with the machine printing parameters to influence the final quality of the manufactured part [8, 16]. The rapid solidification of the material may contain pores, while the interlayer bonding depends on the energy transferred as well as the diffusion of the material. Understanding the physics of the process that leads to defects is crucial, as it helps in the prediction of the defects, allowing the manufacturers to implement quality assurance strategies by selecting the appropriate sensors, feedback, and inspection methods that help in the reduction of defects [36].

The textures that form on the surfaces are the result of the physics of layer-wise deposition, resulting in textures that are fundamentally different from those that form in subtractive manufacturing processes. These relationships between the process conditions and the resulting surfaces allow for the prediction of surface-sensitive properties, including fatigue and tribology performance. Structural integrity represents the integration of all the quality factors, including the absence of critical defects, the microstructure, and the surfaces that are suitable for the application. It must be understood that in order to achieve the desired level of structural integrity, there must be thorough consideration of the parameter selection, the processes, and the validation that occurs after the processes. Defect mitigation must be achieved through the understanding of the relationships that exist between the physics of the processes and the resulting defects, as well as the implementation of quality assurance programs

that are aimed at the detection of the relevant defects that form in the processes, through the selection of the relevant sensors that can be used in the processes.

2.7 Certification and Safety Implications

From the point of view of certification and safety, the existence of defects poses major challenges in the industrial acceptance of additive manufacturing processes. The regulatory guidelines of the aerospace, medical, and automotive industries require proof of the integrity of the material, dimensional accuracy, and mechanical reliability of the manufactured products [3,37]. In the context of the uniqueness of many additive manufactured products, which are produced in small quantities, the applicability of destructive tests is not feasible, and therefore, in-situ monitoring as well as post-process inspection is necessary for the certification of the products [38]. The inability to address the problem of defects may lead to the failure of the products, which may negatively influence the confidence of industries in the applicability of additive manufacturing processes.

3.0 Additive Manufacturing Processes and Their Defect Signs

The basics of additive manufacturing processes and their defect signs are discussed in this section.

3.1 Powder Bed Fusion

Powder Bed Fusion (PBF) techniques, such as selective laser melting (SLM) and electron beam melting (EBM), involve the use of a powerful source of energy that is used to selectively fuse powder in the fabrication of parts. It is an ultra-sensitive technique with respect to heat gradients, scan strategies, and powder characteristics [8, 10]. In Powder Bed Fusion, rapid heating and cooling result in rapid thermal cycles that may result in residual stresses, cracks, and distortion, which may compromise structural integrity. Defects such as lack of fusion may be caused by insufficient energy input, while overuse of energy may result in keyhole porosity and vapourisation-induced void defects [20]. Powder characteristics such as powder size, powder shape, and powder flowability have an additional effect on the generation of defects. Defect generation is a complex function of printing parameters, process parameters, and material properties. Surface textures of Powder Bed Fusion parts are characterised by the presence of partially melted powder particles that are bonded to the surface of the part, especially on features that are facing downwards and vertical surfaces.

Post-process surface treatments can reduce roughness (usually 5-15 μm Ra for optimised conditions), although it remains much greater than machined surfaces. Singh *et al.* [39] reported that in powder bed fusion, insufficient laser energy and scanning approach could result in porosity, keyhole flaws, and incomplete fusion. The growing use of computational modelling and machine learning to forecast defect development and adjust process parameters offers a big step forward in tackling these difficulties and reducing defect creation.

3.2 Directed Energy Deposition

In DED techniques such as laser-based or wire-based DED, input material is required into a melt pool using a concentrated energy source. The constant inputting of new material is associated with problems in terms of adhesion, heat management, and precision in terms of geometry [16]. The larger melt pool, as a result, is more prone to residual stress as well as heat distortion, thereby affecting integrity. Components fabricated using DED techniques are known to display anisotropic structures, with defects such as porosity, lack of fusion, as well as interlayer defects being common when printing parameters such as deposition rates, energy input, and traverse rates are not appropriately controlled [29]. In addition, this technique is prone to environmental influences, such as shielding gas flow rates, which may affect oxidation. The surface texture associated with DED-fabricated components is known to be rougher when compared to Powder Bed Fusion techniques. The layer height is larger, with a "weld bead" texture that may require machining.

3.3 Extrusion-Based Processes

In extrusion-based polymer additive manufacturing, fused filament fabrication (FFF), also known as fused deposition modeling (FDM), is utilised, wherein thermoplastic filaments are deposited layer by layer, leading to defects mainly due to poor interlayer adhesion, the creation of voids, and dimensional inaccuracies, which are generally due to the variation of the temperature of the nozzle, feed rate, as well as layer alignment [9,28]. Figure 7 illustrates the classification of FFF-induced defects in extrusion-based additive manufacturing.

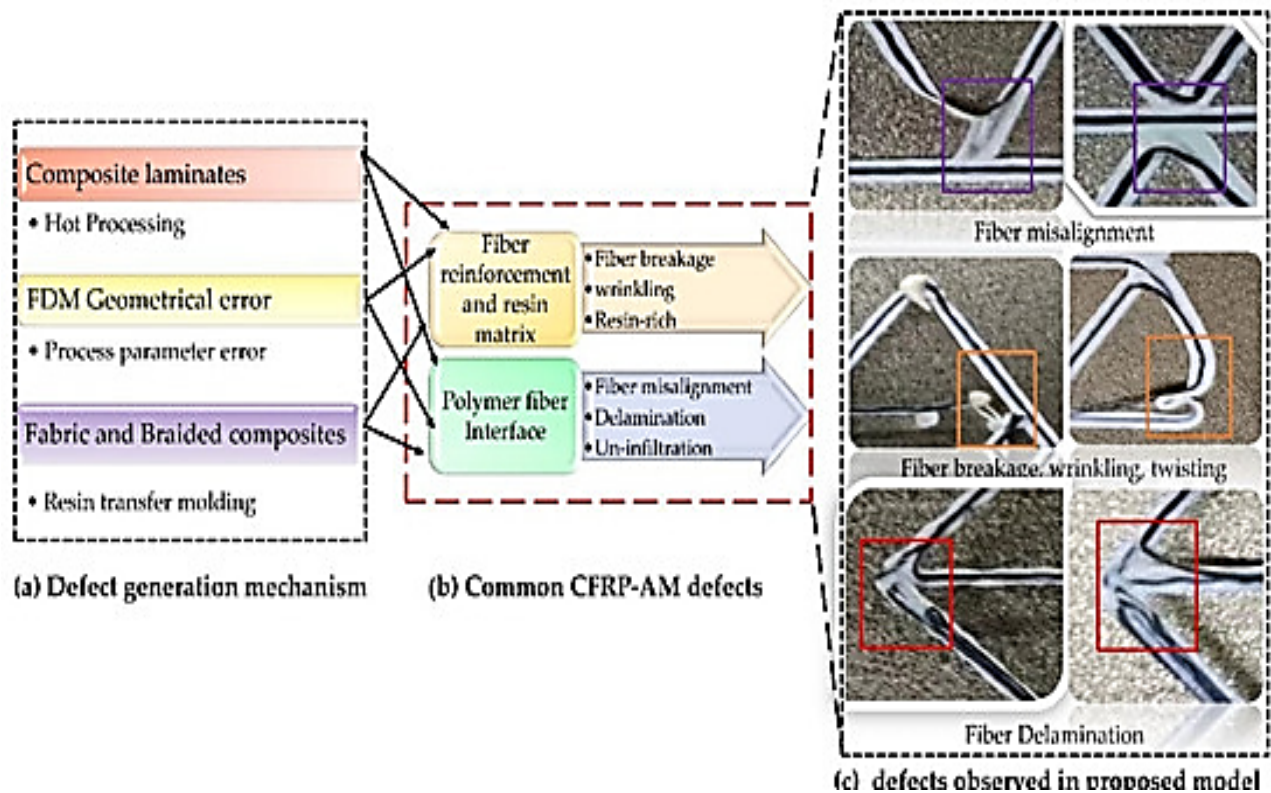


Figure 7: Classification of FFF-Induced Defects in Extrusion-Based Additive Manufacturing [9,40]

Sun et al. [28] have identified several factors that affect the formation of voids in extrusion-based fabrication. In extrusion-based fabrication, the temperature of the extrusion process directly impacts the viscosity and flow behavior of the thermoplastic material. If the extrusion temperature is low, the thermoplastic material may not melt and flow sufficiently to bond with adjacent filaments. On the other hand, if the extrusion temperature is excessively high, the material may degrade. In addition, the printing speed is another factor that may impact the formation of voids in extrusion-based fabrication. If the printing speed is excessively high, the extruded filament may not have sufficient time to bond with previously printed layers. This may result in poor bonding between layers and increased porosity in the printed part [28]. In addition, improper layer height and bead width may impact the degree of overlapping between adjacent filaments. The surface textures of FDM fabricated parts are characterised by the presence of layer lines and the space between the roads of the filament. Although aesthetically unique, these surface textures are prone to stress concentrations and can entrap contaminants for applications requiring cleanability. Post-processing techniques can greatly improve surface smoothness. Defect formation in extrusion-based manufacturing techniques can be minimised by optimising the interrelated printing parameters, and, in the near future, in-situ monitoring techniques for detecting anomalies in layer formation.

3.4 Vat Photopolymerization Processes

Photopolymerisation techniques such as Stereolithography (SLA) and Digital Light Processing (DLP) involve the curing of resins using light sources. The limitations of the photopolymerisation techniques include delamination of the parts created, incomplete curing of the resins, and surface texture irregularities, which are dependent on the intensity of the light used, the curing time, the viscosity of the resin, and the inhibition of oxygen at the surface of the resin [15]. Unlike FDM technology parts, which are anisotropic in nature due to the differences between the layers created, the 3D printer using SLA resin technology can produce isotropic parts with high integrity due to the covalent bonding between the resin components as the parts are created. As the resin is in its 'green state,' which is semi-reacted, the resin contains polymer groups that can bond with each other, making the parts isotropic and watertight [34]. The surface texture of the parts created using the SLA technology is very smooth compared with the surface texture of the parts created using other AM technologies, with the lines created by the layers being almost invisible if the parts are created at the right layer heights.

This smooth surface finish not only contributes to the enhancement of the aesthetic value of the part but also to the functionality, as it removes any stress concentrators and minimizes any friction in moving assemblies. The printing parameters for vat photopolymerization include layer thickness, exposure time, intensity, and lift speed. These printing parameters are required to be balanced in such a manner that proper curing is achieved without any signs of overcuring, which leads to inaccuracies in dimensions.

4.0 In-Situ Monitoring: Fundamentals, Techniques, and Challenges

In-situ monitoring has the potential for identifying circumstances that result in critical defects before these defects become irreparable for structural integrity. It has the feedback required for adaptive control and optimization of the printing processes. Layer-wise image detection has the potential for identifying irregularities that could result in defects or affect the quality of surface textures. Real-time awareness has the potential for intervention in the prevention of defect formation.

4.1 Fundamentals of In-Situ Monitoring

In-situ monitoring of the process of additive manufacturing is the observation of the process of additive manufacturing in real time, which helps in the prediction of defects that may occur during the process of manufacturing [10, 13]. The range of in-situ monitoring of the process of additive manufacturing is wide, as it involves the observation of various parameters, including the thermal, optical, acoustic, and spectroscopic properties of the process of additive manufacturing. Unlike the post-process inspection of the process of additive manufacturing, the in-situ monitoring of the process of additive manufacturing helps the manufacturers predict the defects that may occur during the process of manufacturing, which is an important aspect of the process of additive manufacturing [16]. The graphical representation of the various disciplines of structural health monitoring is shown in Figure 8.

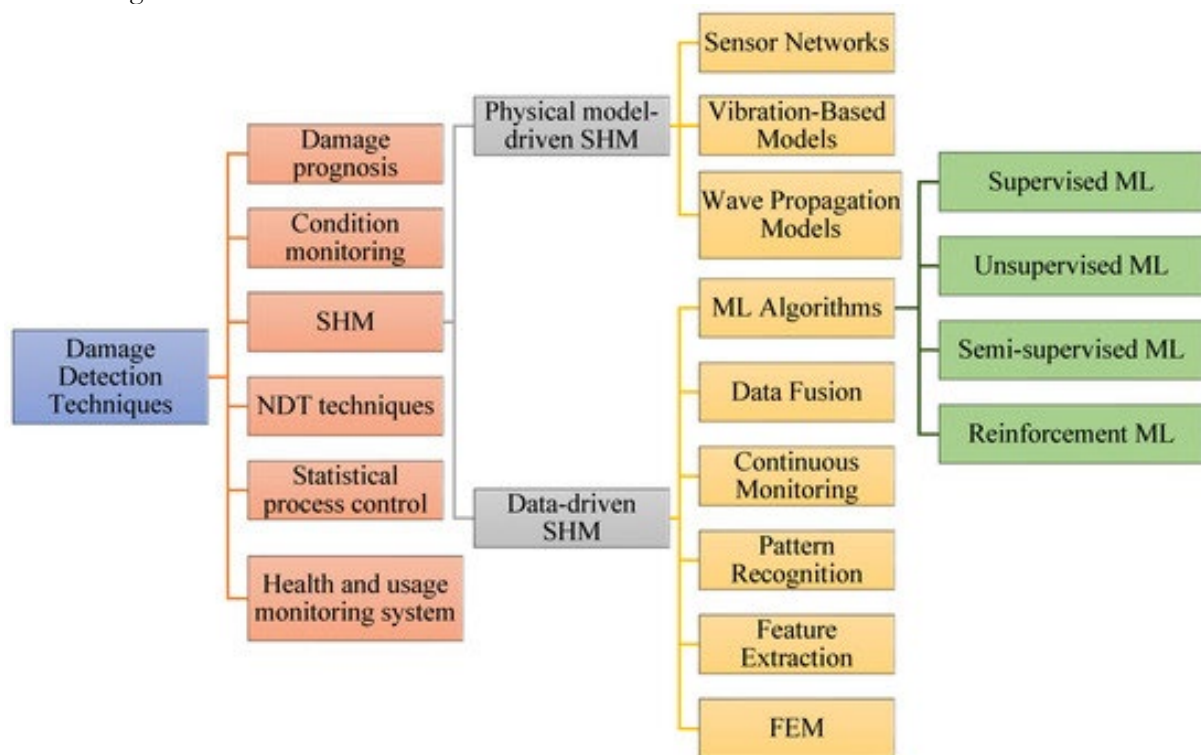


Figure 8: Graphical Depiction of the Diverse Disciplines Employed in Structural Health Monitoring (SHM) for Identifying Damage [41]

4.2 Sensor Technologies for In-Situ Monitoring

Optical Monitoring: Optical cameras and high-speed imaging systems are commonly applied for the monitoring of the melt pool, the formation of spatters, and the development of layer-wise surface features [13]. These systems may also be able to detect unusual occurrences such as irregular track geometry, balling, and unusual surface features that may affect the textures formed on the surfaces. Machine vision algorithms are also becoming more effective in the detection of unusual features, including those that may be classified as defects, from the optical monitoring systems [27]. These are some of how the formation of defects may be mitigated.

Thermal Monitoring: Infrared cameras and pyrometers are commonly applied in the measurement of temperature distribution during the processing of the material. These systems may be able to detect unusual temperature distribution, including overheating, underheating, and unusual cooling rates, that may be associated with the formation of defects [14]. The characteristics of the melt pool may also be applied in the validation of the printing parameters, ensuring that the actual temperatures during the printing process match the temperatures that were established during the development of the printing process.

Acoustic Monitoring: Acoustic emission sensors are used for detecting the stress waves produced during the formation of cracks, delamination, and other processes in the material during processing [17]. Acoustic sensors provide high-resolution monitoring and are able to detect transient defect events that may not be detected by

optical or thermal methods. Acoustic monitoring is also useful in detecting material cracking and delamination, as these directly affect the material's structure.

Spectroscopic Monitoring: Optical emission spectroscopy and laser-induced breakdown spectroscopy are some of the techniques that provide information on the composition, vapourisation, and formation of the plasma during the processing of the material [10]. These techniques are able to detect changes in the composition, as well as the instability in the processing, that may affect the material's properties and the formation of defects. Table 1 shows the comparison of non-destructive and destructive techniques for detecting and analysing material defects. Table 2 presents the sensor performance comparison.

Table 1: Summary of Defect Characterization and Monitoring Techniques in Advanced Manufacturing [42-44]

Technique	Description	Advantages	Limitations	Challenges	Future Opportunities
Optical Microscopy	Visualizes surface features with high spatial resolution.	High spatial resolution. Surface defect detection.	Limited penetration depth. Time-consuming analysis. Sample preparation alters defect distribution.	Subsurface Defects: Detection and characterization of defects beneath the surface domain [42].	Advanced Characterization Techniques: Development of 3D imaging and multi-modal approaches for comprehensive defect analysis.
Electron Microscopy	Provides detailed imaging of surface and internal structures.	High spatial resolution. Surface- and internal-defect analysis.	Vacuum requirements. Specialized sample preparation. Potential alteration of defect morphology.	Effect on Structural Integrity: Implications of defect location for component strength and performance [43].	Innovative Inspection Methods: Integration of advanced sensing technologies for enhanced defect detection.
Acoustic Microscopy	Uses sound waves to detect subsurface defects non-destructively.	Non-destructive subsurface-defect detection.	Limited penetration depth. Requires sophisticated signal processing.	Impact on Performance: Effects of defects within the material thickness on mechanical properties [44].	Data Analytics and ML: Utilization of ML algorithms for automated defect detection and classification.
Electromagnetic Techniques	Utilizes electromagnetic fields for defect detection.	Potential for non-destructive defect detection.	Effectiveness may be limited by material properties. Requires specialized equipment and expertise.	Quality-Assurance Challenges: Limitations of conventional techniques for defect detection and characterization [42].	Innovative sensor design and material optimization for enhanced defect-detection capabilities.

Table 2: Comparison of Performance Indicators for In-Situ Monitoring Sensors

Sensor Type	Spatial Resolution	Temporal Resolution	Cost (USD)	TRL	Major Disadvantage	Primary Defect Detected
Optical camera (coaxial)	10-50 μm per pixel	1-10 kHz	\$5k-\$20k	6	Measures surface; no subsurface measurements	Lack of fusion/balling
High-speed camera	5-20 μm per pixel	10-100 kHz	\$20k-\$100k	5	Data volume/TB per build	Spatter/melt pool dynamics

Infrared pyrometer	50-200 μm spot size	1-100 kHz	\$2k-\$10k	7	Measurements at a single point	Temperature abnormalities
Thermal imaging camera	30-100 μm per pixel	10-100 Hz	\$10k-\$50k	6	Slower than an infrared pyrometer	Thermal map/hotspots
Acoustic emission sensor	N/A/time domain	1-10 MHz	\$1k-\$5k	4	Signal noise	

4.3 Monitoring for Structural Integrity Assessment

In-situ monitoring for structural integrity assessment is based on detecting situations that are known to cause defects that affect mechanical properties [17].

Melt pool characteristics: The size, shape, and temperature of the melt pool are related to consolidation quality and lack-of-fusion defects. Uniformity in melt pool geometry is desirable, while irregularities may indicate problems. Thermal histories: The temperature that each part of the part has been subjected to is essential in determining residual stress, microstructure, and potential cracking. Monitoring this can help predict areas that are susceptible to a lack of integrity. Layer uniformity: Uniform layers with complete fusion between adjacent layers or tracks are essential in achieving full density and isotropic properties. Optical monitoring can be used to observe irregularities in track geometry that may cause lack-of-fusion defects. Acoustic events: Cracking and delamination produce characteristic sounds that can be monitored in real time, thereby providing instant feedback on the lack of structural integrity.

4.4 Monitoring for Printing Parameter Validation and Control

In-situ monitoring plays an important role as a validation and control mechanism for the printing parameters. Even though nominal values of the printing parameters may have been established during process development, actual conditions may differ during actual process implementation due to differences in material properties, equipment conditions, and environmental conditions [14]. Verification of the actual process conditions by monitoring to compare with the desired process parameters. Thermal monitoring may verify the actual conditions of the melt pool temperature range, while optical monitoring may verify the actual conditions of the track geometry due to the actual conditions of the hatch spacing and scanning speed. Adaptive control: during monitoring, when actual conditions deviate from the nominal conditions, the printing parameters may be adjusted to maintain a state of stability in the process. For example, when the actual conditions of the melt pool temperature deviate from the nominal conditions, the actual conditions of the laser power may be adjusted to compensate. In process signature analysis, the correlation between process parameters and process signature provides useful knowledge to optimise the process.

4.5 Monitoring for Surface Texture Characterization

In-situ monitoring of surface textures can detect early signs of undesirable surface texture generation [10]. Layer-wise images can be used to monitor the following surface textures. Stair-stepping effects: In cases where the layer thickness is such that steps are formed on inclined surfaces, in-situ monitoring can be used to detect undesirable heights of steps, which may require parameter adjustment and part orientation. Surface irregularities: In cases where blisters, gaps, and bumps are formed on the surface, in-situ monitoring can be used to detect such surface texture generation. Overhang quality: In cases where surfaces are oriented in the downward direction and are more prone to surface texture generation and overhangs, in-situ monitoring can be used to ensure that the support structures and parameter adjustments are generating desirable surface textures. Colour and translucency: In cases where polymers are used in additive manufacturing, undesirable variations in colour and translucency may be detected.

4.6 Sensor Integration Challenges

Though there are a number of challenges associated with integrating this technology with additive manufacturing. The sensors should be able to operate within the harsh conditions found in the build chamber, with exposure to high temperatures, spatter, dust, as well as intense light emission [10]. The position of the sensors is also essential, with optical or thermal sensors being positioned correctly relative to the melt pool. On the other hand, acoustic or vibration sensors should be attached to the build platform or frame to obtain reliable signals. There is also a need to ensure that there is minimal interference with the actual process by the sensors. The addition of sensors should not interfere with the actual process, with minimal effects on the cooling rate [16].

4.7 Data Characteristics and Interpretation Constraints

In-situ monitoring can generate high volumes of high-frequency data streams, which provide opportunities as well as limitations in defect detection. Thermal cameras, high-speed optical sensors, and acoustic detectors can generate gigabytes of data per build, which calls for the development of sophisticated data processing and analysis techniques [10,16]. The data can also be noisy and multidimensional, requiring the development of sophisticated techniques such as data filtering and feature extraction to identify the relevant signals related to the defect or abnormalities in the manufacturing process [18]. Furthermore, the relationship between the raw data from the sensors and the final product quality can be indirect and nonlinear, requiring the development of sophisticated techniques to relate the raw data to the final product quality. [17] argued that the integration between additive manufacturing and electronic printing is gaining momentum due to the development of machine learning and artificial intelligence techniques to control the manufacturing processes. Machine learning algorithms can be used to analyze the data from the sensors in real-time to identify patterns related to the development of defects.

4.8 Industrial Readiness and Standardization

In June 2022, a workshop on in-situ monitoring, sponsored by ASTM International and NASA, was held to bring together experts from various sectors, such as government, industry, and academia, to evaluate ISM technology and its application in qualification and certification [10, 45]. The objective was to identify the research and development requirements for the advancement of ISM technology readiness. It has been observed that, despite the advancement in research, the efficiency and reliability of in-situ monitoring systems depend on the type of process, sensors, and methods of data interpretation [10]. Standardisation activities are in their initial stages, with the F42 committee of ASTM International aiming to achieve consensus on data format, calibration, and performance metrics for in-situ sensors [6].

5.0 Post-Process Defect Detection: Non-Destructive and Destructive Evaluation Techniques

The basics of post-process defect detection in additive manufacturing processes, with non-destructive evaluation techniques, are discussed in this section.

5.1 Role of Post-Process Inspection in AM Quality Assurance

The post-process defect detection and characterisation techniques remain a vital part of the quality assurance process in additive manufacturing [36]. The application of non-destructive testing (NDT) techniques yields accurate information on internal defect states and dimension conformity, thereby confirming defect states in real-time monitoring [6,15]. Nevertheless, post-process defect detection is often regarded as being time-consuming, costly, and not appropriate for real-time decision-making, thereby calling for alternative strategies rather than standalone solutions [15]. Rather than considering in-situ and post-process defect detection as being mutually exclusive, the current evidence suggests that they are complementary techniques, with in-situ monitoring being used to identify potential problem areas, while post-process techniques are used to confirm defect states.

5.2 X-Ray Computed Tomography

X-Ray Computed Tomography (CT), on the other hand, is widely regarded as the gold standard in detecting internal defects in additively manufactured products. Computed Tomography is a 3D imaging technique that is able to provide a 3D image of internal defects, enabling quantification of porosity, lack of fusion defects, crack patterns, and dimensional inaccuracies [8]. This technique is especially useful in complex geometries when interior details are inaccessible to other inspection techniques.

Wu et al. [32] used micro-analysis CT to study the development of defects in 3D-printed thermoplastic-based composite materials as a function of processing parameters using Computed Tomography analysis. The application of Computed Tomography inspection has some drawbacks, such as long scanning time, equipment cost, difficulties in inspecting large-sized parts, as well as difficulties in detecting certain defects, such as tight cracks and delamination with small opening displacement [19].

5.3 Ultrasonic Testing

Ultrasonic testing involves the detection of internal defects through the analysis of the characteristics of the propagation of ultrasonic waves [15]. It has already gained acceptance in the field of conventional manufacturing processes and has also started being applied in the field of AM processes [46]. Laser ultrasonic testing was applied as a non-contact method for the inspection of internal defects in 3D-printed carbon fiber composite cylindrical structures. By analyzing the propagation of ultrasonic waves, the detection of defective areas, such as the presence of voids, delamination, and changes in material density, was achieved. Defective areas in the material were identified through the alteration in the propagation characteristics of the ultrasonic waves, including the velocity, attenuation, and reflection of the waves, thereby locating the defective area in the material accurately.

Ultrasonic phased arrays provide improved inspection techniques through the application of electronic beams, allowing the material to be scanned [47]. Ultrasonic testing involves the application of coupling media or direct contact with the material under consideration, but the interpretation of the results may be difficult in the case of anisotropic material properties.

5.4 Thermographic Inspection

Infrared thermography measures surface temperature variations using active and passive heating techniques to identify subsurface defects. It is highly sensitive to delamination, large voids, and areas with low thermal conductivity [48]. Active thermography employs the use of external heat sources such as lamps, lasers, or hot air to induce thermal variations, while passive thermography relies on natural temperature variations occurring during or after the processing step. Pulsed thermography and lock-in thermography are advanced techniques with high defect detection capabilities.

5.5 Surface Metrology and Optical Methods

Surface metrology methods, such as optical profilometry, laser scanning, and structured light scanning, enable accurate characterisation of surface topography, dimensional accuracy, and geometric deviations [9]. These methods are critical for establishing dimensional conformity and for detecting defects that occur on the surfaces of materials. Microscopy and scanning electron microscopy allow for high-resolution examination of surfaces, fiber orientation, and microstructural features of materials [33]. These techniques were used to examine fiber distribution, orientation, and matrix-fiber interfaces for fiber-reinforced composites.

5.6 Dye Penetrant and Metallographic Methods

Dye penetrant inspection is one technique that offers a simple way to identify surface-breaking defects in non-porous materials at low cost. It is done by applying a penetrating dye and then removing the excess before applying the developer to identify the defect locations [15]. Metallographic inspection, although destructive in nature, is very important in verifying the microstructural properties of the material, grain size and orientation, as well as defect concentrations in the development and qualification of the processes [35]. It involves the destruction of the component by sectioning and polishing to facilitate the microscopic examination of the internal features.

6.0 Comparative Analysis and Integration Frameworks

The comparative analysis and integration frameworks are explained as follows:

6.1 Comparative Assessment of Detection Techniques

From recent literature, the correlation of Additive Manufacturing (AM) defects with detection techniques can be classified as in-situ (during production) and ex-situ (after production) techniques. Comparative correlation of commonly occurring additive manufacturing defects with in-situ monitoring and ex-situ detection techniques, with observations on detection capabilities and limitations as described in Table 3.

Table 3: Mapping of Additive Manufacturing Defects to Detection Techniques [42,43]

Defect Type	Description / Impact	In-Situ Monitoring Techniques	Post-Process Detection Techniques	Observations
Porosity / Gas Voids	Small internal voids that reduce strength and fatigue life	Melt pool imaging, Acoustic emission, Optical tomography	X-ray CT, Ultrasonic testing	Sub-surface porosity is often missed by optical sensors; NDT confirms internal distribution.
Lack of Fusion / Incomplete Melting	Layers or regions are not fully bonded, causing weak spots	Thermal imaging, High-speed cameras	X-ray CT, Dye penetrant, Metallography	In-situ thermal signals can indicate potential regions; post-process confirms the defect.
Cracking / Hot Cracks	Cracks from residual stress or thermal gradients	Acoustic emission, High-speed imaging, Temperature monitoring	Ultrasonic testing, Metallography	In-situ acoustic sensors detect crack initiation; post-process

Defect Type	Description / Impact	In-Situ Monitoring Techniques	Post-Process Detection Techniques	Observations
Residual Stress / Distortion	Warping, stress accumulation, leading to dimensional inaccuracies	Laser displacement sensors, Thermal imaging	X-ray diffraction, Strain gauges, CMM	verifies full crack propagation. In-situ thermal monitoring identifies stress trends; post-process quantifies the exact deformation.
Surface Roughness / Irregularities	Affects dimensional accuracy, post-processing cost	Layer-wise imaging, Optical profilometry	Optical profilometry, 3D laser scanning	In-situ cameras detect layer defects; post-process scanning validates final geometry.
Microstructural Inhomogeneity	Variations in grain structure affecting mechanical properties	Limited direct detection; may infer via thermal signatures	Metallography, Microhardness testing, SEM	Primarily post-process; some proxies are possible with in-situ thermal or melt pool monitoring
Delamination / Layer Separation	Layers detach, reducing structural integrity	Acoustic emission, Thermal imaging	X-ray CT, Ultrasonic testing	Early signs are detectable in situ via acoustic or thermal anomalies; confirmed post-build

6.2 Critical Comparison: In-Situ Monitoring vs. Post-Process Detection

Table 4 provides a critical comparison of in-situ monitoring and post-process detection approaches across key features relevant to industrial implementation.

Table 4: Critical Comparison of In-Situ Monitoring and Post-Process Detection [42-44]

Feature	In-Situ Monitoring	Post-Process Detection
Feedback Timing	Real-time during build	After completion
Defect Correction Possible	Yes (process adjustment)	No (scrap or rework only)
Defect Localization	Approximate (process signatures)	Precise (spatial mapping)
Data Volume	Very high (continuous streaming)	Moderate (discrete inspection)
Data Interpretation	Requires sophisticated data processing and AI	Uses standard inspection data
Detection of Sub-Surface Defects	Limited (surface/subsurface only)	Excellent (internal visualization)
Cost	High initial investment, but can save on scrap	High final cost if defects are found late
Integration Complexity	Challenging to integrate into the workflow	Relatively simpler to add to the workflow
Standardization	Emerging (ASTM F42 activities)	Established (traditional NDT standards)
Certification Acceptance	Limited (supporting evidence)	Primary (qualification evidence)

6.3 Integrated Monitoring and Inspection Frameworks

Instead, as the current evidence shows, these two approaches, in-situ and post-process, are not mutually exclusive, but rather complement each other [15]. In this regard, integrated approaches combine the benefits of

real-time monitoring with the benefits of post-process inspection, as discussed by Shen et al. [16] in the context of integrating in-situ monitoring with post-process inspection in additive manufacturing, along with the challenges and future perspectives of the same. The different components of integrated approaches are as follows:

Data Fusion: The combination of data obtained from various in-situ sensors with the data obtained from post-process inspection helps in the correlation of the process with the final product quality. The accuracy of the machine learning model may improve by training the model with the combined data obtained from in-situ sensors and post-process inspection. **Feature Extraction:** The identification of certain process signatures that may be correlated with the occurrence of certain types of defects may improve the accuracy of the inspection system by reducing false alarms.

Closed-Loop Control: The feedback obtained from in-situ sensors may help in the control of the process during the actual building of the component, which may improve the accuracy of the inspection system by reducing developing defects. This demands the development of robust algorithms that address the problem of anomaly detection as well as parameter selection. **Qualification Frameworks:** The integrated data may contribute to the qualification of the part by offering proof of the stability of the process as well as the defect-free fabrication during the entire construction process [36].

6.4 Data-Driven Defect Prediction Using Machine Learning

The application of machine learning and artificial intelligence for defect detection has progressed rapidly in additive manufacturing [17]. The application of data-driven methods has several benefits, including **Pattern Recognition:** Machine learning algorithms have shown promise in recognizing patterns from multi-modal sensor data that may be correlated with defects. This could potentially improve the detection of defects. **Predictive Modeling:** Machine learning models have shown potential for building predictive models for defect detection based on historical and sensor data. This could allow for predictive modeling of defects. **Feature Engineering:** Machine learning could help improve feature engineering for defect detection by automatically extracting features from sensor and process data. This could help improve the detection of defects. In the work [18], recent advances in condition monitoring and fault diagnosis using machine learning and IoT. The study also reviewed recent applications of these methods for additive manufacturing. In another research, Wu et al. [2] reviewed physics-informed machine learning methods and their applications for condition monitoring and anomaly detection.

Machine learning (ML) technology has seen rapid development in defect detection in AM, going from post-process evaluation to real-time forecasting. Table 5 summarizes the particular architectures and their uses.

Table 5: Particular Architectures and Their Uses

Architecture	Application	Reported Performance	Limitation
Convolutional Neural Network (CNN)	Melt pool image classification (PBF)	92-96% accuracy for porosity vs. lack-of-fusion [27]	Requires labeled images; fails on unseen machine geometries
U-Net (segmentation CNN)	Layer-wise anomaly segmentation	87% IoU (intersection over union) for spatter detection [42]	Computationally intensive (0.5 sec/layer)
Long Short-Term Memory (LSTM)	Thermal history prediction for residual stress	RMSE <15°C for next-layer prediction [18]	Requires long training sequences (>1000 layers)
Autoencoder (unsupervised)	Anomaly detection without labeled defects	78% recall at 5% false positive rate [17]	Cannot classify defect type; only flags "abnormal."
Random Forest / XGBoost	Feature-based classification from sensor data	F1-score of 0.85 for cracking prediction [44]	Requires hand-crafted features; less accurate than deep learning

7.0 Case Studies: Defect Detection in Fiber-Reinforced Polymer Composites

The case studies of defect detection in fiber-reinforced polymer composites are presented below.

7.1 Additive Manufacturing of Fiber-Reinforced Polymer Composites

The addition of fiber reinforcement in thermoplastic additive manufacturing has greatly contributed to the structural properties of 3D printed polymer components [23, 49]. The benefits of fiber-reinforced polymer composites produced via additive manufacturing, with regard to their stiffness, strength, and weight efficiency, are much better when compared to unreinforced polymer materials. In their study, Wong et al. [50] discussed the

state-of-the-art design methodologies in the additive manufacturing of fiber-reinforced polymer composites, focusing on the importance of integrated design approaches that consider fiber-reinforced polymers, process planning, and manufacturing constraints. The authors discussed the advancements in multiscale topology optimization and micromechanics modeling, as well as the mechanical properties of the produced composites, which are not as good as those produced by conventional manufacturing methods.

7.2 Defect Challenges in Fiber-Reinforced Additive Manufacturing (AM)

One of the challenges identified is defects that occur during the formation of fiber-reinforced materials using the layer-by-layer approach, as illustrated in Figure 9. The defects identified include porosity, low bonding between layers, fiber waviness, fiber breakage, and poor bonding between fibers and matrix [23,25]. The defects occur mainly due to instability of the process, insufficient temperature, and inadequate planning of tools. **Void Formation:** The formation of voids may occur due to insufficient consolidation of deposited filaments, insufficient compaction pressure, or inadequate thermal conditions during printing [49]. The formation of voids may reduce the load-carrying capacity of the printed product. **Fiber-Matrix Bonding:** The bonding between the fiber and matrix is critical for enhancing the mechanical properties of fiber-reinforced composites. The impregnation of fibers with molten polymer during printing may be inadequate, resulting in poor bonding between the fiber and matrix. This may cause fiber pull-out, micro-cracks, and reduction of structural stiffness [22]. **Fiber Misalignment:**

The variation of printing speeds, movement of nozzles, and fiber feeding mechanisms may cause fiber waviness and fiber misalignment. [50] highlighted that fiber orientation errors had a significant impact on the efficiency of the transfer of loads from the matrix to the reinforcement fibers. **Interlayer Adhesion:** Poor interlayer adhesion was found to cause anisotropic mechanical properties, in which the strength of the composite material would vary depending on the direction of the applied load [23]. This was found to be a major problem in the application of composite materials in additive manufacturing techniques.

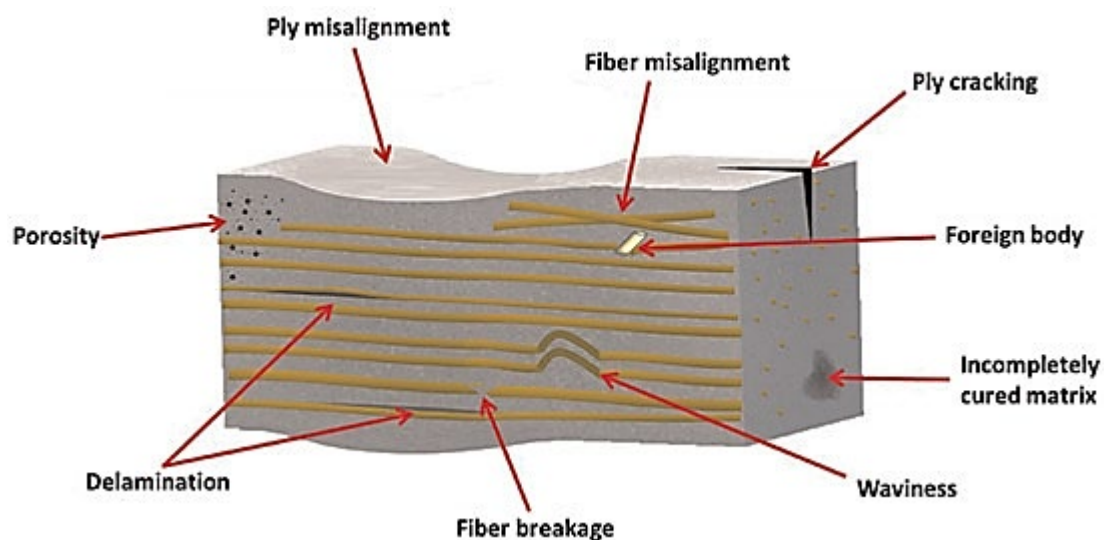


Figure 9: Most Frequent Manufacturing Defects in Additive Manufacturing of Composites [48]

7.3 Laser Ultrasonic Testing of CFRP Composites

A study by Lee *et al.* [46] was conducted on the effectiveness of the laser ultrasonic test method in the detection of defects that occur during the manufacturing process of 3D printed carbon fiber reinforced cylindrical composite structures. The laser ultrasonic test method generates ultrasonic waves using a pulsed laser, while the surface vibrations of the structure are detected by another laser interferometer. This is highly effective in the inspection of complex geometries, especially when dealing with delicate structures comprising composites. The study proved that the laser ultrasonic test method is effective in the detection of defects inside printed composite structures by analysing the propagation of ultrasonic waves.

7.4 Continuous Fiber Reinforced Thermoplastic Composites

Chacón *et al.* [21] studied the effects of FDM processing parameters on the mechanical properties of CFRTP composite parts. The parameters identified as having significant effects on the mechanical properties include layer height, as increasing layer height may cause poor compaction and bonding, as well as raster orientation, as improper orientation may cause poor fiber orientation with respect to the load. [22] studied the potential of using additive manufacturing on CFRTP composite materials based on PEEK thermoplastics, with significant potential being identified. The main problems identified include voids, poor bonding, and fiber orientation.

7.5 Comparative Assessment of Additive Manufacturing Technologies for Quality-Critical Applications

Table 6 provides a comprehensive comparison of FDM, SLA, and SLS technologies across key performance indicators relevant to quality-critical applications.

Table 6: Comparative Assessment of FDM, SLA, and SLS Technologies [34]

Feature	Fused Deposition Modeling (FDM)	Stereolithography (SLA)	Selective Laser Sintering (SLS)
Process Principle	Extrusion of thermoplastic filament	Laser curing of liquid photopolymer	Laser sintering of powder
Isotropy	Low (anisotropic)	High (isotropic)	Medium/High (nearly isotropic)
Watertightness	Poor (requires post-processing)	Excellent (chemically bonded layers)	Good (with appropriate design)
Surface Finish	Visible layer lines	Smooth, injection-molded quality	Slightly rough/grainy
Dimensional Accuracy	Moderate ($\pm 0.5\%$)	High ($\pm 0.15-0.3\%$)	High ($\pm 0.3\%$)
Support Structures	Required	Required	Not required
Typical Defects	Layer delamination, voids, warping	Incomplete curing, delamination	Porosity, sintering defects
Material Options	Thermoplastics (ABS, PLA, nylon, composites)	Photopolymers (engineering, dental, castable)	Engineering thermoplastics (nylon, TPU, composites)
Post-Processing Requirements	Support removal, surface finishing	Washing, post-curing, support removal	Powder removal, surface finishing optional
Applications	Prototyping, concept models	Functional prototyping, tooling, dental, jewelry	Functional parts, end-use production
Industrial Readiness	Mature (consumer to industrial)	Mature (professional)	

7.6 Watertightness and Isotropic Properties

The concept of isotropy versus anisotropy is also an important aspect that is often addressed in 3D printing, as 3D printing builds objects in layers. Finished 3D printing objects may exhibit differences in strength depending on the direction in which the object was built, i.e., in X, Y, and Z axes [34]. It is known that 3D printing objects created using the FDM 3D printing technology are anisotropic in nature, as the bonds formed in the lines are much stronger than the bonds formed in the layers, as there are spaces left in the layers formed by the rounded lines of the 3D printing material, and the layers are not able to form bonds with the lines [34]. On the other hand, 3D printing objects created using the resin 3D printing technology are isotropic in nature, as the resin material reacts with the resin components during the 3D printing process and forms covalent bonds, and when the object is in the 'green state,' it can form bonds with the next layer, as the resin material contains polymerizable groups that form bonds with the next layer.

On a molecular level, there is no difference between X, Y, or Z planes, thereby ensuring that parts with predictable mechanical properties are critical in applications such as jigs and fixtures, end-use parts, and functional prototyping [34]. The 3D printers using SLS create parts that are mostly isotropic. As opposed to FDM, in SLS, particles that are already in contact with each other are sintered, thereby ensuring that particles are fused with both particles in the same plane as well as those in the layer below. Nevertheless, as various materials take varying times to hold heat and remain in a semi-sintered state, isotropy is also dependent on various powders [34]. The comparison of 3D printed enclosures tested under pressure is shown in Figure 10.

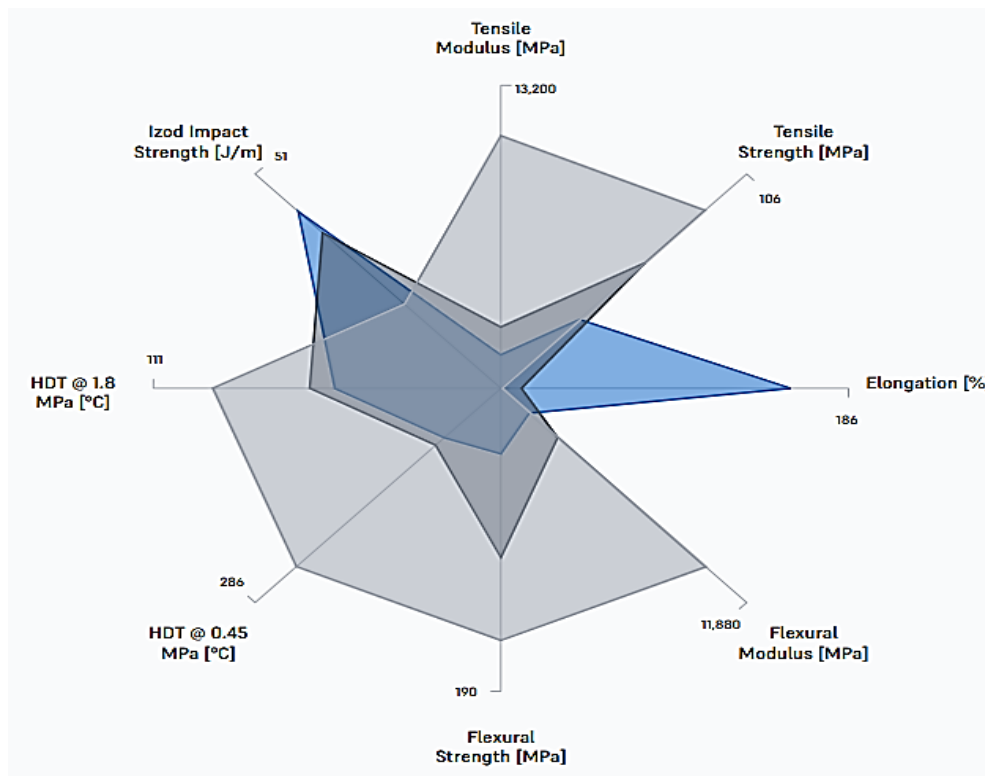


Figure 10: Comparison of 3D Printed Enclosures Tested Under Pressure: FDM (failed immediately), SLA (watertight to high pressure), and SLS (watertight to moderate pressure) [51]

7.7 Mechanical Property Comparison

Table 7 compares the mechanical properties of common materials across FDM, SLA, and SLS technologies, providing guidance for material selection based on performance requirements.

Table 7: Mechanical Properties of Common 3D Printing Materials [34]

Material	Technology	Tensile Strength (MPa)	Tensile Modulus (Stiffness) (GPa)	Elongation at Break	Flexural Modulus (GPa)	Impact Strength (Notched Izod) (J/m)	Heat Deflection Temp (HDT @ 0.45 MPa) (°C)	Best for / Applications
PLA	FDM	50–60	3.5	5–6%	3.0–4.0	16–25	55 °C	Aesthetic models, static prototypes
ABS	FDM	35–40	2.2	10–30%	2.3	200–250	95 °C	Durable consumer goods, enclosures
Nylon (PA6/12)	FDM	60–80	1.5	>100%	1.2	200–400	90–140 °C	High-wear gears, bearings, and friction parts
CF-Nylon	FDM	80–100+	6.0–10.0	2–4%	8	40–60	150–160 °C	Structural parts, extreme stiffness

Material	Technology	Tensile Strength (MPa)	Tensile Modulus (Stiffness) (GPa)	Elongation at Break	Flexural Modulus (GPa)	Impact Strength (Notched Izod) (J/m)	Heat Deflection Temp (HDT @ 0.45 MPa) (°C)	Best for / Applications
Polycarbonate (PC)	FDM	60–70	2.3	5–10%	2.2	50–80	135–145 °C	High-stress parts, heat resistance
PEEK	FDM	90–100	3.8	30–40%	3.9	50–80	150–260 °C	Metal replacement, extreme environments
PEKK	FDM	80–93	3	2–6%	3	30–40	150–160 °C	Aerospace, chemical resistance, low outgassing
Tough 2000 Resin	SLA	40	1.8	79%	1.7	25	70 °C	Sturdy jigs, ABS-like functional parts
Tough 1500 Resin	SLA	34	1.5	155%	1.4	42	66 °C	Springy parts, snap-fits, living hinges
Tough 1000 Resin	SLA	26	0.9	180%	0.8	72	55 °C	Squeezable parts, high-impact tooling
Rigid 10K Resin	SLA	88	11	2%	9.9	20	238 °C	Injection molds, glass-filled simulation
Rigid 4000 Resin	SLA	69	4.1	5%	3.4	23	77 °C	Thin walls, stiff brackets, housings
High Temp Resin	SLA	49	2.8	2%	2.8	17	238 °C	Casting molds, fluid/airflow components
Nylon 12 Powder	SLS	50	1.9	11%	1.6	32	171 °C	General purpose, great detail, housings
Nylon Tough Powder	SLS	42	1.5	25%	1.1	60	161 °C	Functional prototypes, snap-fit enclosures
Nylon 12 GF Powder	SLS	38	2.8	3–4%	2.4	36	170 °C	Robust jigs, fixtures, enclosures, and

Material	Technology	Tensile Strength (MPa)	Tensile Modulus (Stiffness) (GPa)	Elongation at Break	Flexural Modulus (GPa)	Impact Strength (Notched Izod) (J/m)	Heat Deflection Temp (HDT @ 0.45 MPa)	Best for / Applications
Nylon Powder	11 SLS	49	1.6	40%	1.4	71	182 °C	replacement parts Ductile parts, thin walls, impact resistance
Nylon CF Powder	11 SLS	69	5.3		4.2	74	188 °C	Lightweight structural parts, high heat

7.8 Implications for Defect Detection Strategy Selection

Technology selection is an important factor that affects the requirements of the defect detection strategy. In FDM, where anisotropy and interlayer adhesion are major concerns, in-situ monitoring of the layer deposition quality and the thermal conditions affecting interlayer adhesion is recommended [28]. In post-process inspection, emphasis should be placed on the interlayer bond integrity and anisotropic properties of the fabricated part. In SLA, where isotropy and watertightness are inherent advantages, in-situ monitoring of the curing completeness of the photo-polymerized material is recommended [34]. In post-process inspection, emphasis may be placed on the dimensional verification of the fabricated part, especially if internal defects are of concern.

In SLS, where powder fusion/sintering is of major concern, in-situ monitoring of the thermal distributions and powder bed conditions is recommended [52]. In post-process inspection, emphasis should be placed on the inspection of the fabricated part using CT or ultrasonic inspection techniques, especially in the detection of internal porosity and lack of fusion defects.

7.9 Future Directions

Even though considerable research progress has been made in the field, the standardization of the in-situ monitoring and defect detection techniques is still in its initial stages. ASTM International F42 committee has started the development of data formats, calibration of sensors, and performance measures; however, comprehensive standards are still needed for the qualification and certification processes using the monitoring techniques [6,45]. [37] published the report on the interagency working group on the qualification and certification of additive manufacturing, digital twin-based failure prediction, and supply chain risks reduction. The integration of various sensing techniques is also promising in terms of defect detection; however, effective techniques for data fusion are still in the development stage [16]. [2] reviewed the physics-informed machine learning techniques with applications in condition monitoring and anomaly detection techniques.

The techniques have promising advantages; however, future studies are needed to develop the physics-informed models specifically related to the defect formation mechanisms in the context of additive manufacturing processes [53-55]. Digital twin techniques have the potential to provide comprehensive control over the processes by using the real-time monitoring data [18,36]. With the expansion of additive manufacturing into various material systems, including ceramics, multi-materials, and functionally graded materials (FGMs), defect detection techniques should develop accordingly [39]. Even though much research has been done on defect detection, closed-loop process control using monitoring information is still limited [10]. The implementation of advanced monitoring and inspection technologies in industries depends on their economic feasibility [35].

8.0 Conclusions

In this critical review, the current state of in-situ monitoring and post-process defect detection in additive manufacturing was discussed, with particular emphasis on the capabilities, limitations, and readiness of the technologies. Defects in additive manufacturing occur at various types and length scales, making it necessary to employ multiple detection solutions instead of a single solution approach. Currently, no single monitoring or inspection method is capable of detecting all types of defects. In-situ monitoring, as an early warning system, needs to be combined with post-process inspection, which is necessary for validation and certification purposes. The

most comprehensive solution is an integrated framework that employs multiple monitoring modalities along with NDT inspection.

The vast amount of data generated by the monitoring sensors in terms of volume, velocity, and complexity makes it necessary to employ advanced data analysis techniques. Machine learning and AI are promising solutions, although they need careful validation. There is a need for standardization of sensor calibration, data formats, and qualification, which is lacking at the current time. ASTM International is working on this, which is necessary for the advancement of the field. Defects in various additive manufacturing processes occur by different mechanisms, making it necessary to employ different detection strategies.

The introduction of reinforcing fibers also creates additional forms of defects, including fiber misalignment, fiber-matrix interfacial issues, and complex void characteristics, necessitating the development of specialized monitoring techniques. The implementation of advanced monitoring techniques must be supported by the quality, scrap, and certification advantages that they provide. Cost-benefit analyses must be carried out to inform investment decisions in industry.

The shift in the application of additive manufacturing from prototyping to the production of safety-relevant parts must be supported by quality assurance techniques. The in-situ monitoring and post-processing detection of defects, when properly integrated and validated, form the basis of certifiable additive manufacturing processes and parts. Further research efforts aimed at addressing the gaps that this review has identified must be pursued to accelerate the industrial adoption of additive manufacturing and broaden the application space for these technologies.

Industrial practice requires the adoption of integrated inspection-monitoring schemes, which can result in a cost reduction for quality assurance of around 40-60% when compared to conventional non-destructive testing conducted exclusively after process completion. On the other hand, academics must focus their efforts on generating ML models that can be applied in general situations through testing on open machine datasets. Regarding standardization organizations such as ASTM, ISO, FDA, and FAA, it is important to create qualification processes that recognise in-situ data as verification of the manufacturing process.

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