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Standard Guide for In-Process Monitoring Using Optical and Thermal Methods for Laser Powder Bed Fusion[1]

This standard is issued under the fixed designation E3353; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This guide provides information on emerging *in-process* monitoring sensors, sensor configurations, sensor data analysis, and sensor data uses for the laser powder bed fusion additive manufacturing process.

1.2 The sensors covered produce data related to and affected by feedstock, processing parameters, build atmosphere, microstructure, part geometry, part complexity, surface finish, and the printing equipment being used.

1.3 The parts monitored by the sensors covered in this guide are used in aerospace applications; therefore, their final inspection requirements for discontinuities are different and more stringent than for materials and components used in non-aerospace applications.

1.4 The metal materials under consideration include, but are not limited to, aluminum alloys, titanium alloys, nickel-based alloys, cobalt-chromium alloys, and stainless steels.

1.5 This guide discusses sensor observation of parts while they are being fabricated. Sensor data analysis may take place concurrently or after the manufacturing process has concluded.

1.6 The sensors discussed in this guide may be used by cognizant engineering organizations to detect both surface and volumetric flaws.

1.7 The sensors discussed in this guide may be used by cognizant engineering organizations to detect process stability or drift, or both.

1.8 The sensors discussed in this guide are primarily configured in staring, co-axial, or mounted configurations.

1.9 This guide does not recommend a specific course of action, sensor type, or configuration for application of in-process monitoring to additively manufactured (AM) parts. It is intended to increase the awareness of emerging in-process sensors, sensor configurations, data analysis, and data usage.

1.10 Recommendations about the control of input materials, process equipment calibration, manufacturing processes, and post-processing are beyond the scope of this guide and are under the jurisdiction of ASTM Committee F42 on Additive Manufacturing Technologies. Standards under the jurisdiction of ASTM F42 or equivalent are followed whenever possible to ensure reproducible parts suitable for NDT are made.

1.11 Recommendations about the inspection requirements and management of fracture critical AM parts are beyond the scope of this guide. Recommendations on fatigue, fracture mechanics, and fracture control are found in appropriate end user requirements documents, and in standards under the jurisdiction of ASTM Committee E08 on Fatigue and Fracture.

NOTE 1—To determine the deformation and fatigue properties of metal parts made by additive manufacturing using destructive tests, consult Guide F3122.

NOTE 2—To quantify the risks associated with fracture critical AM parts, it is incumbent upon the structural assessment community, such as ASTM Committee E08 on Fatigue and Fracture, to define critical initial flaw sizes (CIFS) for the part to define the objectives of the NDT.

1.12 This guide does not specify accept-reject criteria used in procurement or as a means for approval of AM parts for service. Any accept-reject criteria are given solely for purposes of illustration and comparison.

1.13 *Units*—The values stated in SI units are to be regarded as the standard. No other units of measurement are included in this standard.

1.14 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.15 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

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[1] This guide is under the jurisdiction of ASTM Committee E07 on Nondestructive Testing and is the direct responsibility of Subcommittee E07.10 on Specialized NDT Methods.

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2. Referenced Documents

2.1 *ASTM Standards:*[2]

E1213 Practice for Minimum Resolvable Temperature Difference for Thermal Imaging Systems

E1256 Test Methods for Radiation Thermometers (Single Waveband Type)

E1316 Terminology for Nondestructive Examinations

E1543 Practice for Noise Equivalent Temperature Difference of Thermal Imaging Systems

E1934 Guide for Examining Electrical and Mechanical Equipment with Infrared Thermography

E2582 Practice for Infrared Flash Thermography of Composite Panels and Repair Patches Used in Aerospace Applications

E2587 Practice for Use of Control Charts in Statistical Process Control

E2862 Practice for Probability of Detection Analysis for Hit/Miss Data

E3023 Practice for Probability of Detection Analysis for $\hat{a}$ Versus a Data

E3045 Practice for Crack Detection Using Vibroacoustic Thermography

E3166 Guide for Nondestructive Examination of Metal Additively Manufactured Aerospace Parts After Build

F3122 Guide for Evaluating Mechanical Properties of Metal Materials Made via Additive Manufacturing Processes

2.2 *ISO/ASTM Standards:*[3]

ISO/ASTM 52900 Terminology for Additive Manufacturing Technologies

ISO/ASTM 52921 Terminology for Additive Manufacturing—Coordinate Systems and Test Methodologies

ISO/ASTM TR 52905 Additive Manufacturing of Metals — Non-destructive Testing and Evaluation — Defect Detection in Parts

2.3 *ISO Standards:*[4]

ISO 10878 Non-Destructive Testing - Infrared Thermography – Vocabulary

ISO 11146-2 Lasers and Laser-related Equipment — Test Methods for Laser Beam Widths, Divergence Angles and Beam Propagation Ratios — Part 2: General Astigmatic Beams

ISO 12233 Photography — Electronic Still Picture Imaging — Resolution and Spatial Frequency Responses

ISO 13372 Condition Monitoring and Diagnostics of Machines — Vocabulary

ISO 17359 Condition Monitoring and Diagnostics of Machines — General Guidelines

ISO 17850 Photography — Digital Cameras — Geometric Distortion (GD) Measurements

ISO/IEC 15775 Information Technology — Office Machines — Method of Specifying Image Reproduction of Colour Copying Machines by Analog Test Charts — Realisation and Application

ISO/TC 108/SC 5 Condition Monitoring and Diagnostics of Machine Systems

2.4 *EN Document:*[5]

EN 16714-2 Non-destructive Testing - Thermographic Testing - Part 2: Equipment

2.5 *MIL Document:*[6]

MIL-STD-150A Photographic Lenses (12 May 1959)

3. Terminology

3.1 *Order of Precedence*—In order of precedence, the following terminologies apply:

3.1.1 For terminology related to general NDT practices, use Terminology E1316.

3.1.2 For terminology related to NDT of metal additively manufactured parts, use Guide E3166.

3.1.3 For terminology related to AM, use ISO/ASTM Terminology 52900.

3.2 *Definitions:*

3.2.1 *build chamber, n*—see terminology ISO/ASTM 52900.

3.2.2 *co-axial configuration, n*—a sensor integrated within the optical path of the laser, such that the sensor's field of view is fixed to the moving position of the laser (or other heating sources considered in future versions of this guide).

3.2.2.1 *Discussion*—Co-axial configuration is also known as *on-axis*, *down-beam*, or *on-axial configuration*. Refer to Section 7 on Melt Pool Monitoring.

3.2.3 *defect, n*—see Terminology E1316.

3.2.4 *flaw, n*—see Terminology E1316.

3.2.5 *flaw characterization, n*—see Terminology E1316.

3.2.6 *indication, n*—see Terminology E1316.

3.2.7 *lack of fusion (LOF), n*—see Guide E3166.

3.2.7.1 *Discussion*—LOF-induced void formation can be sub-categorized based on their formation directionality: as horizontal LOF, in which adjacent scan tracks within the same layer have insufficiently melted or fused together, forming a void, and vertical LOF, in which scan tracks in a new layer do not fully melt or fuse previous or lower layers.

3.2.8 *layer imaging, n*—a process monitoring technology applied to powder bed fusion where images are captured and recorded of the build layers before or after, or both, laser exposure, powder spreading, or material consolidation.

3.2.8.1 *Discussion—Layer imaging* utilizes one or more cameras in *staring configuration*.

3.2.9 *melt pool mode, n*—a characteristic of the melt pool size, shape, and dynamic behavior, primarily dependent on the input laser energy density.

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[3] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org.

[4] Available from International Organization for Standardization (ISO), ISO Central Secretariat, Chemin de Blandonnet 8, CP 401, 1214 Vernier, Geneva, Switzerland, https://www.iso.org.

[5] Available from www.en-standard.eu.

[6] Available from http://everyspec.com.

3.2.9.1 *Discussion*—Melt pool modes include *conduction mode* and *keyhole mode*. Refer to 7.2.2.

3.2.10 *melt pool monitoring, n*—the continuous measurement of process signatures associated with perturbations, anomalies, or trends stemming from the laser (or other heat source) induced molten metal pool.

3.2.11 *porosity (keyhole), n*—see Guide E3166.

3.2.11.1 *Discussion*—This guide differentiates from contextual use in Guide E3166 in that it considers the in-process keyhole pore formation (as opposed to post-build inspection in Guide E3166). Keyhole porosity is created when the laser energy density is sufficiently high to cause a deep melt pool resulting in hydrodynamic instability of the surrounding liquid metal and subsequent collapse, leaving a void at the root of the keyhole. Like generic voids and gas porosity, keyhole porosity causes a part to be less than fully dense.

3.2.12 *process signature, n*—potentially observable physical phenomenon that occurs during the AM fabrication process and is potentially correlatable to part quality metrics.

3.2.13 *self-healing, n*—phenomena where potential defects are re-melted during AM fabrication which thus eliminates the defect's existence in the final part.

3.2.14 *solidification crack, n*—also known as *hot crack*, cracks that initiate when rapid cooling at the fusion boundary of a melt pool causes high thermal strain and separation of material that is not adequately filled by molten material.

3.2.15 *spatter, n*—particles ejected away from the vicinity of a melt pool.

3.2.15.1 *Discussion*—Also known as *ejecta*, spatter or ejecta can originate from within the melt pool or from surrounding powder. It is caused by multiple different physical phenomena, but can generally be sub-categorized into *hot spatter* or *cold/cool spatter*. Refer to 4.7.3.1(1).

3.2.16 *staring configuration, n*—a type of sensor configuration wherein a non-contact sensor is mounted within or outside the build chamber, such that its field of view is fixed with respect to the machine coordinates (see ISO/ASTM 52921).

3.2.16.1 *Discussion*—Also known as *fixed position*, *lateral configuration*, *off-axial configuration*, or *paraxial configuration*.

3.2.17 *voids, n*—see Guide E3166.

3.3 *Abbreviations:*

3.3.1 The following abbreviations are adopted in this guide:

3.3.1.1 *CCD*—Charge-coupled Device

3.3.1.2 *CMOS*—Complimentary Metal-Oxide Semiconductor

3.3.1.3 *CT*—Computed Tomography

3.3.1.4 *FOV*—Field of View

3.3.1.5 *IFOV*—Instantaneous Field of View

3.3.1.6 *LED*—Light Emitting Diode

3.3.1.7 *LOF*—Lack of Fusion

3.3.1.8 *LPBF*—Laser Powder Bed Fusion

3.3.1.9 *MPM*—Melt Pool Monitoring

3.3.1.10 *PBF*—Powder Bed Fusion

3.3.1.11 *R&D*—Research and Development

3.3.1.12 *SFT*—Spatial Frequency Response

3.3.1.13 *SPC*—Statistical Process Control

3.3.1.14 *TFOV*—Total Field of View

4. Significance and Use

4.1 Metal additive manufacturing has broadened design space, enabling production of more complex and customized products. Additive technology along with the broadened design space is pushing the limits of inspection capabilities and has led to challenges in process and product qualification, verification, certification, etc. In-process monitoring technologies have been developed to help address these challenges.

4.2 In-process monitoring in AM is emerging from the realm of Research and Development (R&D). As such, there are not yet well-established procedures for incorporating AM process monitoring within a qualification or certification framework outside of a specific company or institution's internal use. Practical application of in-process monitoring data spans multiple disciplines and parts of the production cycle, each with well-established practices, terminology, expectations, etc. This guide draws on these where appropriate.

4.3 *Inspection and Statistical Process Control (SPC)*—A primary motivation for using in-process monitoring technologies is to aid in process and product qualification, verification, certification of AM components that are increasingly difficult to inspect. AM process monitoring functions can be broadly separated into two categories of application: in-process inspection and process control. In-process inspection refers to the identification of in-process signatures that correlate to the formation of physical flaws and defects in additively manufactured component. This is discussed further in 5.2 on Flaw Detection. Statistical Process Control (SPC) encompasses measurement or observation of process signatures or metrics associated with the stability or repeatability of the additive manufacturing process. This is discussed further in 5.3 on Statistical Process Control (SPC). Real-time feed-forward or feed-back control methods and techniques may be considered subcategories under process control, and can make use of the same in-process monitoring measurement tools. Currently, these concepts and techniques are still largely under research and development not generally implemented in commercial LPBF systems. They are not discussed further in this guide.

4.4 *Production and Development Uses*—Production of finished components using additive manufacturing requires some combination of inspection to ensure the component meets design requirements for the ultimate product functionality and process qualification. Both inspection and process control applications of in-process monitoring may be integrated into an overall product or process qualification, verification, or certification strategy, or a combination thereof, in the production environment. In-process monitoring tools are also valuable in the development both of the additive process and build design, providing support for engineering decisions on parameter selection (for example, laser power, scan speed) for new materials, scan strategy, part geometry, part placement on an AM build platform, etc. A prerequisite to SPC is establishing the normal variation of the process which can be evaluated using in-process monitoring tools during process development.

4.5 *Economic Justification*—In-process monitoring can be economically justified through its contribution to cost reduction and yield improvements in addition to its value to the additive manufacturing enterprise as an element of an overall process or product qualification, verification, or certification strategy, or a combination thereof. For high value products, in-process monitoring has been shown to reduce the scrap fraction rate by at least 10 % according to recent literature.[7] The realization of the cost/part reduction in the scrap fraction rate over time is dependent on the diagnostic capability of the in-process monitoring strategy as measured in false alarm (false positive) and undetected defect (false negative) performance. Further in-process monitoring can produce per part cumulative yield improvements through enabling process engineering diagnosis capabilities within part manufacturing such that SPC charts can be tuned to optimize the system's diagnostic performance.

4.6 *Identifying Part Quality from Process Signatures*—Ultimately, final part quality metrics and associated mechanical or functional performance of AM parts are of greatest concern. Guide E3166, pertaining to ex-situ NDT, identifies two correlations of interest: process-flaw correlation and flaw-property correlation. In the context of this guide, measurements of material flaws or properties are considered *part quality metrics*. As noted in Guide E3166, part quality metrics may be correlated to the process or process parameters, such as laser power, laser scan speed, etc. as shown in Fig. 1. *In-process monitoring* pertains to the observation and measurement of *process signatures*, or observable phenomena that occur during the AM process, for example, electromagnetic emissions from the melt pool, acoustic emissions, etc. Process signatures are correlated to process parameters. While process parameters are generally commanded or set point values, process signatures provide a measured voice of process. Process signatures may also be correlated to part quality metrics, as shown in Fig. 1. As part of a product inspection and validation strategy, in-process monitoring aims to utilize the correlation between these process signatures and part quality metrics. In-process monitoring can thus be used to in conjunction with or in-lieu of post-process inspection methods (for example, NDE).

4.6.1 *Process Signature Taxonomy*—Many different terms have been used in AM to describe process signatures or part quality metrics in the context of in-process monitoring (for example, defect, fault, flaw, anomaly, imperfection, etc.). The following provides a high-level taxonomy used in this guide to further define and categorize deleterious process signatures in AM process monitoring. As noted in 4.3, in-process monitoring is primarily used as part of an overall quality plan, either as a supplement to or replacement of traditional component inspection methods (for example, NDE) or to enable statistical process control. These two functions are mapped to corresponding taxonomies are mapped in Fig. 2.

4.6.2 For the in-process enabled inspection case, this taxonomy builds upon established standards or work items (see Terminology E1316, Guide E3166, and ISO/ASTM TR 52905).

(1) Indication (Terminology E1316): In an in-process enabled inspection, a process signature observed from the in-process monitoring data that is evidence of a potential material flaw is deemed an *indication* (Terminology E1316). As in traditional NDE, the indication is subject to interpretation as a *false indication*, *nonrelevant indication*, or *relevant indication* (Terminology E1316). A *relevant indication* (Terminology E1316) is indicative of a material flaw and requires further evaluation as to whether the flaw is acceptable or the part must be rejected based on the requirements of the component.

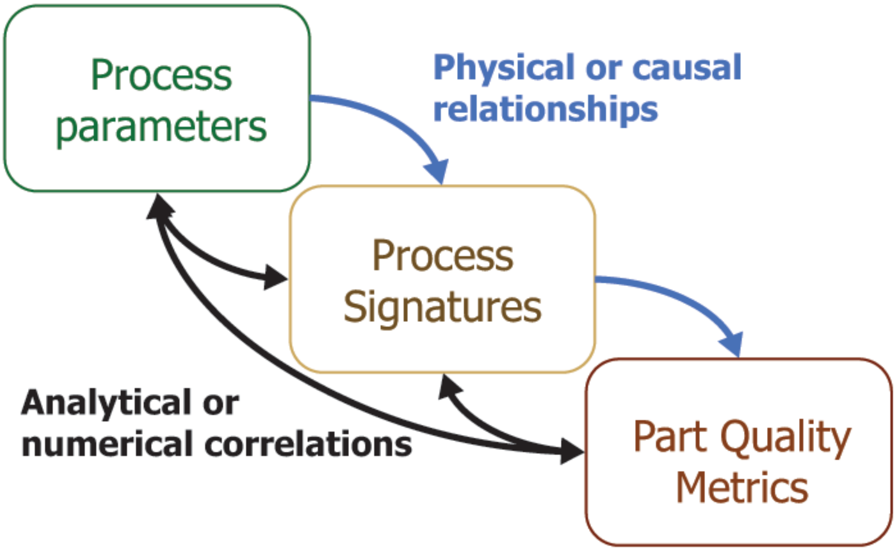

FIG. 1 General Schematic of AM In-process Monitoring High-level Objectives for Inspection to Identify the Correlations, Through Analytical or Numerical Methods, that Relate Process Signatures to Part Quality Metrics and Utilize These as Part of a Broader Inspection or Part Validation Strategy

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[7] Colosimo, B. M., Cavalli, S. and Grasso, M. "A cost model for the economic evaluation of in-process monitoring tools in metal additive manufacturing," *International Journal of Production Economics*, Vol 223, 2020, 107532, ISSN 0925-5273.

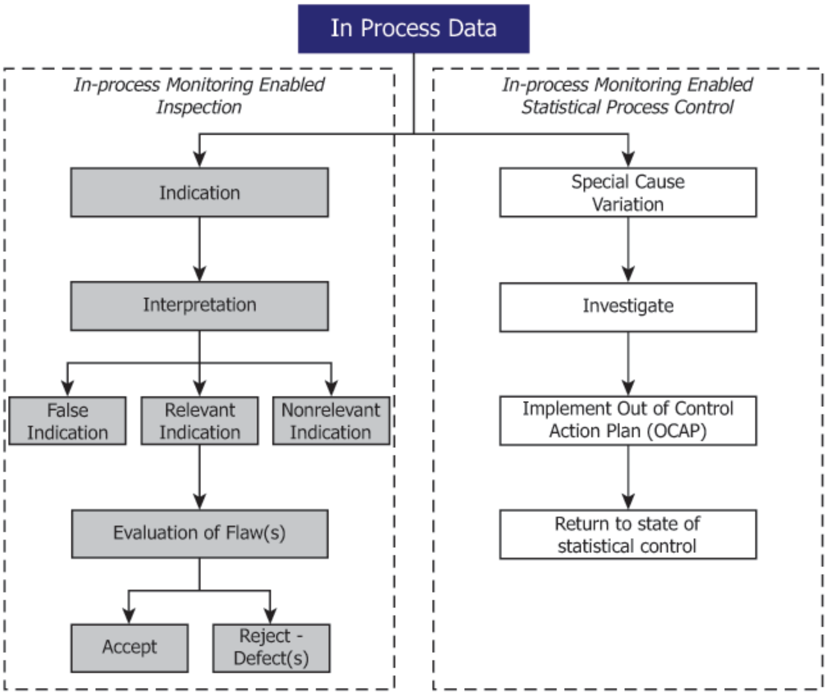


FIG. 2 Description of Higher-level Terms Relating an Observation of Process Signatures From In-process Monitoring for Inspection and Statistical Process Control (SPC) use Cases

(2) Flaw (Terminology E1316): A flaw is an imperfection or discontinuity, the formation of which may be detectible by in-process monitoring, but is not necessarily rejectable.

(3) Defect (Terminology E1316): One or more flaws whose aggregate size, shape, orientation, location, or properties do not meet specified acceptance criteria and are rejectable.

4.6.3 Statistical process control (SPC) uses statistical methods to improve quality by reducing the variability of one or more process outputs. For in-process monitoring enabled statistical process control, one or more process signatures are the outputs of the process to which SPC is applied. Process variation may be classified in one of two categories, *common cause variation* or *special cause variation*.

(1) Common Cause Variation (Practice E2587), also referred to as *chance variation*, is inherent random variation in the process which is predictable within statistical limits. An additive manufacturing process may be said to be in a *state of statistical control* when only common cause variation is observed (Practice E2587).

(2) Special Cause Variation (Practice E2587), also referred to as *assignable cause variation*, associated with a process disturbance or upset. Special cause variation may be associated with a spike, shift, trend, or change in variability of the in-process signal.

4.7 *Additive Manufacturing Flaws and Flaw Formation Mechanisms*—Understanding how in-process flaws and defects form during fabrication is critical to the instrument design, data analysis or interpretation, and general application of AM in-process-monitoring. The following describe flaws that may exhibit in-process, and may be targeted for observation by in-process monitoring instruments. The following is not a comprehensive list or categorization of in-process flaws or defects, but is meant as a guide to better understand how the most commonly observed or understood flaws and defects may relate to in-process monitoring. Additional details regarding in-process defect and flaw formation are provided in regards to each measurement system modality discussed starting in Section 7.

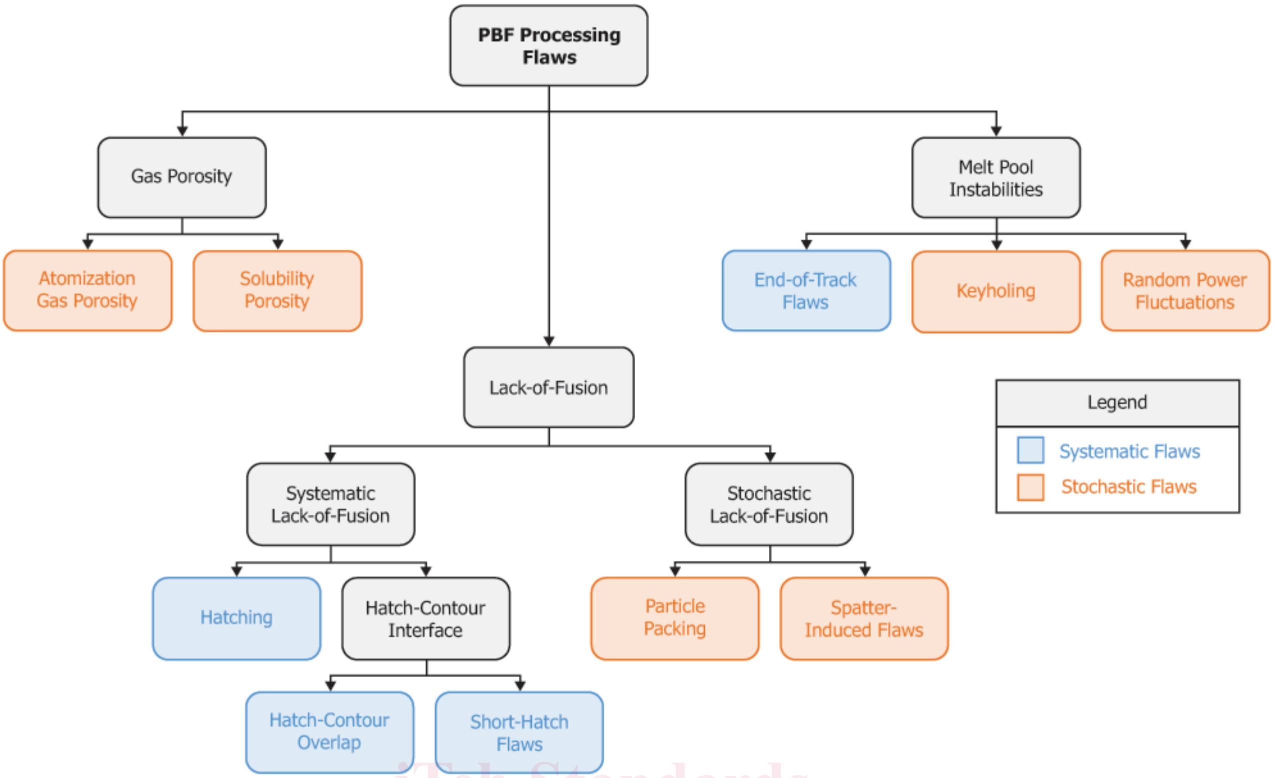
4.7.1 *Stochastic versus Systemic Defect Formation*—Systematic defects are voids resulting from input processing parameters and build plan. In contrast, stochastic flaws result from conditions that are not systematically controlled (that is, are a consequence of random or statistical processes), as shown in Fig. 3.

4.7.2 *In-process Defects:*

4.7.2.1 *Void Formation*—The term voids (*voids* in Guide E3166, or synonymous with *discontinuity* in Terminology E1316) includes any material discontinuity within a part that is not a designed feature. This includes pores and cracks. While the methods of formation of voids is not always discernible in post-process inspection, their formation and corresponding signatures may be observable and distinguishable via in-process monitoring.

(1) Pores (Guide E3166)—Pores are material discontinuities that are distinguishable from cracks, but may similarly act as stress concentration or crack initiation sites. Cracks, viewed in 2D, are a discontinuity with an extremely low aspect-ratios. Pores and cracks may be surface-connected. In the context of this guide, pores are further sub-categorized from description in Guide E3166 based on their formation mechanisms and potential signatures:

(a) Keyhole Porosity (Guide E3166 and ISO/ASTM TR 52905)—Keyhole porosity is related to instability in the liquid melt pool, and typically occurs under relatively high laser



NOTE 1—Reprinted from *Additive Manufacturing*, Vol 36, Snow, Z., Nassar, A. R., and Reutzel, E. W., "Review of the formation and impact of flaws in powder bed fusion additive manufacturing," 2020, 101457, https://doi.org/10.1016/j.addma.2020.101457, with permission from Elsevier.

FIG. 3 Example Organization and Categorization of Some Flaws Observable in a Laser Powder Bed Fusion (LPBF) Process, Categorized by 'Systematic' or 'Stochastic' Formation

energy density (7.2.2). Observation of keyhole porosity generally requires melt pool monitoring to capture a keyhole event, or related melt pool signature (7.2.2). This can be generally (but not directly) related to observation of a deeper, wider, or brighter melt pool. Individual keyhole pores are roughly an order of magnitude smaller than the melt pool, or approximately the scale of typical LPBF powder (for example, 10's of µm). Specific instrument design criteria, and statistical correlation between in-process monitoring observations and keyhole pore formation are still a matter of research and development.

(b) Gas Porosity (Guide E3166)—Gas porosity, thought to result from gas entrapped within a powder particle during manufacturing of the powder or interstitial gases released due to reduced solubility upon solidification, is generally not considered to be observable via current in-process monitoring techniques, since the pores are incorporated into the powder material and do not typically reach the surface.

(2) Lack of Fusion (LOF) (Guide E3166 and ISO/ASTM TR 52905)—LOF pore formation can be subcategorized as either horizontal LOF or vertical LOF (ISO/ASTM TR 52905). Generally, only horizontal LOF pores or events are observable on the top surface of the fabricated layer via in-process monitoring. However, observation of multiple LOF events within the same region over multiple layers may be indicative of formation of vertical LOF pores.

(3) Hatching LOF—A horizontal LOF stemming from incomplete melting and wetting of adjacent scan tracks.

(4) Hatch-contour Overlap and Short-hatch Flaw—A horizontal LOF stemming from incomplete melting and wetting at the intersection of a contour and infill laser scan tracks.

4.7.2.2 *Cracking:*

(1) Delamination Cracking—Delamination occurs when layers within an AM build separate from one another forming a cavity or crack, often due to excessive residual stress buildup during fabrication in conjunction with poor design of the part or support materials, or both, or selection of appropriate AM build parameters. This most often occurs at the interface between a solid part structure and support structure, support and substrate, or the solid part and substrate. During AM fabrication, delamination cracking may be observed as increasing elevation of the part above new powder surface, or acoustic signatures that occur during cracking events.

(2) Solidification Cracking (or Hot Cracking)—Solidification-cracking occurs when rapid cooling at the fusion boundary of a melt pool causes high thermal strain and separation of material that is not adequately filled by molten material. Solidification cracks may occur during solidification, or very shortly after, and can be enlarged or exacerbated by subsequent heating and cooling cycles. Certain materials are more susceptible to hot cracking than others, and various filler materials may be introduced to the alloy to reduce susceptibility. Combination of process parameters, and their effect on melt pool shape and resultant thermal gradients in and around the melt pool, can contribute to the likelihood of solidification

cracking. Solidification cracks may be observable via acoustic signatures, but are generally too small and occur for indication via optical means.

4.7.3 *In-process Flaws:*

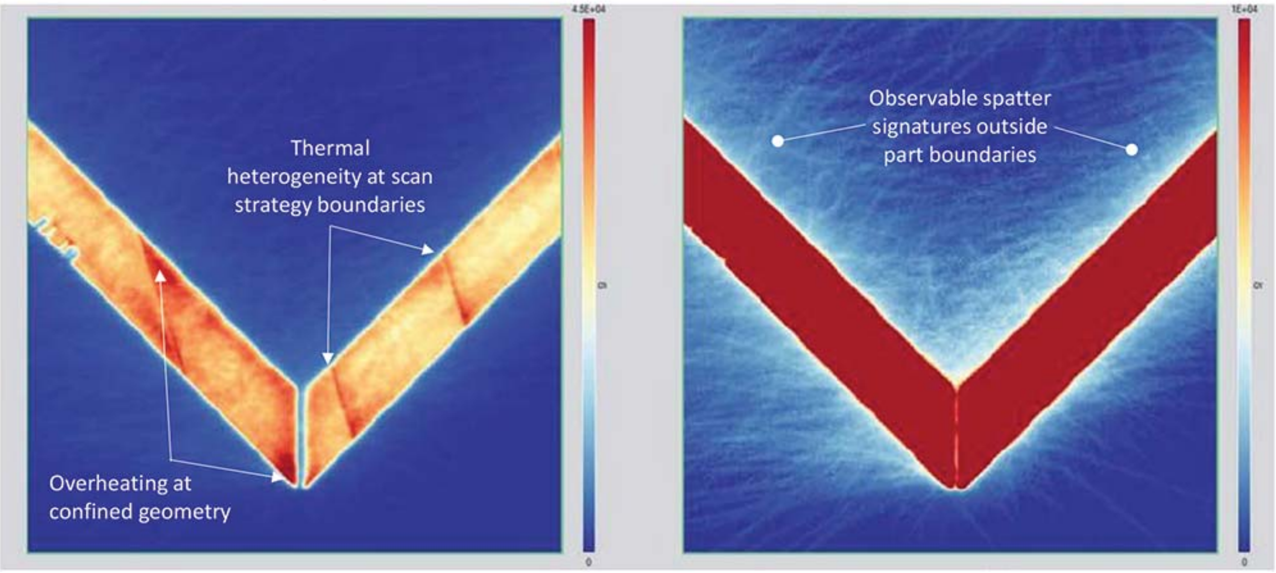
4.7.3.1 *Overheating, Overmelting, or Thermal Heterogeneity*—Due to the dynamically moving heat sources used during AM processing, some regions of a fabricated part can experience excessive heat accumulation and elevated temperatures relative to the rest of the part volume. This can generally be attributed to one or two factors: (*1*) combination of scan-strategy and layer geometry which causes excessive laser exposure over a confined area within the layer (Fig. 4); (*2*) laser exposure over a confined region, where the relatively low thermal conductivity of the surrounding powder inhibits conduction of heat away from the melt pool. Local overheating can be observed via several process signatures: (*1*) Increased size, temperature, or brightness of a melt pool (see 7.2.5 on Melt pool 'intensity'); (*2*) discoloration or 'scorching' of the overheated region, and (*3*) humping, elevation, abnormally smooth/fluid, or generally different surface structure and topography in the overheated region (see Section 8 on Layer Imaging).

(1) Excessive Spatter/Ejecta—At the LPBF melt pool scale, many particles can be observed escaping (or ejected) from the vicinity of the melt. These particles initiate from several phenomena. Melt ejection occurs when evaporation-induced recoil pressure exceeds the surface tension pressure within the melt pool, causing molten droplets to escape. Spatter particles also result from powder particle entrainment within the evaporation-induced gas flow. Hot spatter particles are formed due to laser- or vapor-induced heating of entrained particles. Relatively frequent, intense, or excessive hot spatter may be targeted by process monitoring instruments (Fig. 4) as an indication of flaw or defect formation, or deleterious fabrication quality.

4.7.3.2 *Powder Layer or Recoating Flaws*—Improper application of metal powder layers during LPBF fabrication can result in part defects. A number of in-process flaws associated with insufficient or improper powder layer formation are known, and are generally easily observed and interpreted. Generally, the source of these flaws can be categorized as stemming from the erroneous recoating process (for example, *skipping, scraping, insufficient powder delivery, part strikes*), part formation errors (*distortion, humping, balling*, or *superelevation*). While many of these flaws may be observable through multiple process monitoring modalities, they are primarily observed through Layer Imaging processes. Refer to Section 8 on Layer Imaging for detailed description of powder layer flaws.

4.7.4 *Speed, Resolution, and Data Considerations*—Speed, resolution, and data considerations specific to each sensor modality will be discussed starting in Section 7. Generally, data rate and storage requirements for process monitoring are relatively high, which largely stems from the multi-scale physics of the AM fabrication process, and the necessity to adequately resolve signatures spatially or temporally.

4.7.4.1 For example, assume a typical 250 mm x 250 mm build area, divided into 0.1 mm x 0.1 mm pixels (2500^2 pixels/layer). Assume a 200 mm build height divided into 0.02 mm layers (10 000 layers/build). This results in 2500^2 pixels/layer × 10 000 layers/build × 1 byte/pixel = 62.5 GB/build. Similarly, in the temporal domain, consider a sensor acquiring data at 100 kHz, over a 36 h build. This results in a 10^5 samples/s × 129 600 s/build × 1 bytes/sample results in



NOTE 1—Barfoot, M. (2020). *Evaluation of In-Situ Monitoring Techniques* (Additive Manufacturing Consortium (AMC) Project Final Report, EWI Project No. 58279CPQ).

FIG. 4 Example From Staring-configuration, Near-infrared (NIR) Spectrum Melt Pool Monitoring Camera. This System Compiles Images from Multiple Camera Exposures and Processes Them Into a Single Image. Left: Image Data Based on 'Integrated' Values, Which Highlight Thermal Heterogeneity Features. Right: Image Data Based on 'Maximum' Value, Which Highlight Spatter or Plume Features

approximately 13 GB/build. These values are only given as typical examples, but indicate the relative volume of data that might be expected to be on the order of 10's of GB per sensor per build.

4.7.5 *Data Reduction or Compression*—Most often, in-process monitoring data size is reduced either in-line during acquisition, or just prior to storage, so that the raw instrument values are not transferred or stored. This is done by processing the data into a reduced-dimension parameter (for example, obtaining a single-value measurand from a 2D image), reducing the indicated or represented resolution (for example, averaging or 'binning' pixels in an image), removing unnecessary data (for example, dark or saturated pixels in an image), employing data compression algorithms (lossy or loss-less), or employing other data reduction methods.

4.7.6 *Data Alignment or Registration*—Data alignment, registration, and visualization considerations specific to each sensor modality will be discussed in Sections 7 – 9. Refer to subcommittee ASTM F42.08 for proposed standards on data alignment and registration.

4.7.6.1 Visualization of in-process monitoring data is typically represented in the spatial domain, such that sensor signals or process signatures derived from those signals are mapped to the spatial position within the 3D part when or where, or both, they were acquired (Fig. 5). Most often, this is represented in three ways: (*1*) *3D part representation*, where signatures or features are mapped to the 3D location within a part, forming digital representation of the part(s), but constructed from process monitoring data; (*2*) *2D layer representation*, where the data is mapped to a plane nominally commensurate with an AM fabrication layer (normal to the build direction); or (*3*) *2D slice representation*, where values or data from a 3D part representation are projected onto a planar slice that is oriented in a direction different than the 2D layer representation.

4.7.6.2 In this manner, the geometric location of those process signatures that may indicate an in-process flaw or defect can potentially be aligned and correlated to the same flaw or defect observed via ex-situ methods (for example, X-ray computed tomography (XCT)). For example, see Fig. 6.

4.7.6.3 Alignment of in-process measured process signatures with part geometry requires additional measurements to obtain information that relates the positioning of the sensor's field of view or sensing area to a coordinate system shared by the machine or parts. For further description of some of the measurement references, refer to ASTM subcommittee F42.08 for proposed standards on data alignment and registration. Some examples of accessory measurements for data alignment or registration are as follows:

(1) Simultaneous Acquisition of Laser/Galvo Position versus Time—Many commercial process monitoring systems enable synchronized acquisition of the laser scan position via the galvanometer (galvo) system in parallel with the process monitoring instruments. This is done either by reading the digital commands (for example, XY2-100 or SL2-100 digital command protocol) sent to the galvanometer, or reading galvo feedback encoder signal, if available. Alignment or registration of process monitoring instrument signals or images is done by directly mapping the sensor signal to the synchronized spatial location (for example, XY position) where it was obtained from the galvo position. This method is widely used for co-axial instrument configurations (for example, melt pool monitoring, Section 7), or single-element detectors that do not provide spatial information (for example, staring configuration photodetector or mounted acoustic sensor).

(2) Reference Scan Pattern—Particularly for staring configuration instruments in a LPBF system, a reference pattern or grid with known geometry can be scanned on a bare substrate, initial layers within a build, or during intermediate layers

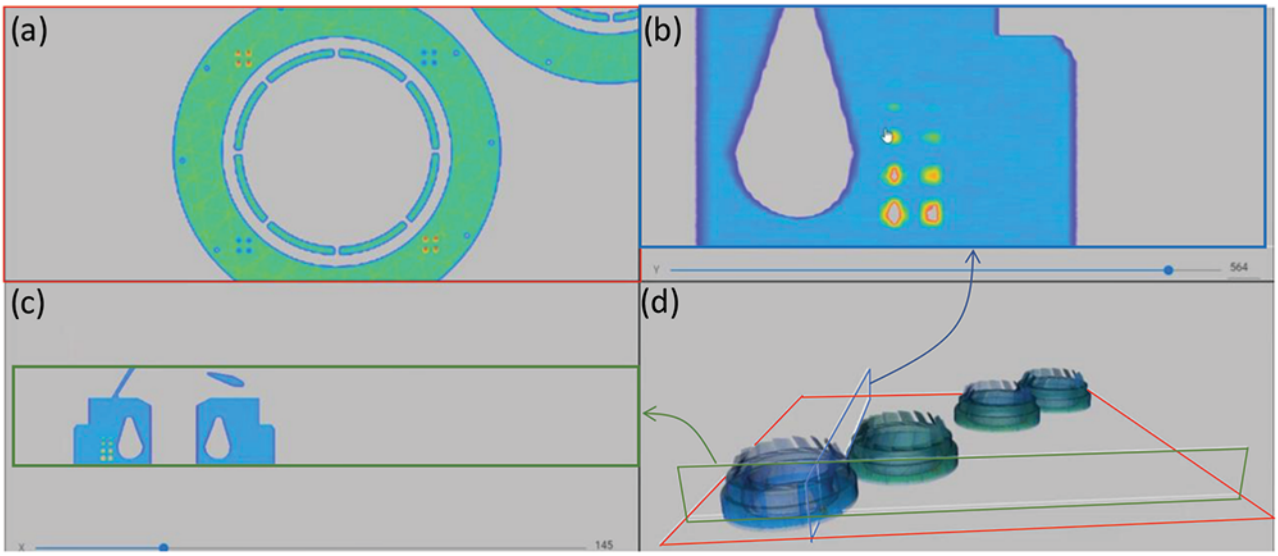
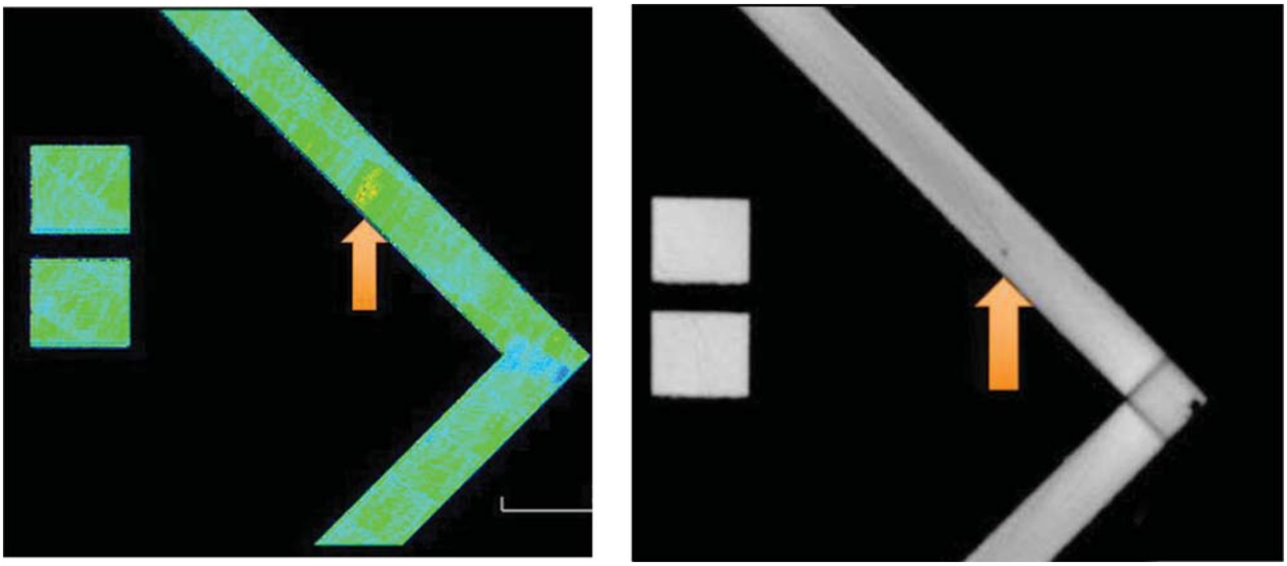


FIG. 5 Example Registration of 1D Process Monitoring Data (Signal versus Time from Melt Pool Monitoring (MPM) Photodetectors in Co-axial Configuration) into 3D Representation, Which Can Then be Projected onto Different Planar Slices (a) 2D Layer Representation (XY Plane), (b) 2D Slice Representation (YZ Plane), (c) 2D Slice Representation (XZ Plane), (d) 3D Part Representation (Orthographic Projection), Showing Location of the 2D Slice Locations



NOTE 1—Barfoot, M. (2020). *Evaluation of In-Situ Monitoring Techniques* (Additive Manufacturing Consortium (AMC) Project Final Report, EWI Project No. 58279CPQ).

FIG. 6 Example Local Anomaly Observed in Co-axial Configuration, Photodetector-based Melt Pool Monitoring (Left), and Corresponding Observation of a Pore Defect (Right) from XCT of the Fabricated Part

within a build. Measurement via the process monitoring sensors may be conducted synchronously with the scan, or immediately after completion. Dimensions of the reference pattern may be known from the commanded reference pattern geometry programmed into the AM machine controller, or via ex-situ measurement by a calibrated dimensional measurement (for example, calipers, optical CMM). Signal or images acquired from the process monitoring instruments may then be mapped or transformed into the coordinates acquired via the measured reference scan pattern.

(3) Reference Target—Similar to the scanned reference pattern, a calibrated dimensional target or artifact may be placed in the field of view or sensing area of the process monitoring instrument(s). For example, an imager may observe a dimensional calibration artifact that has been oriented with the machine or part coordinate system (Section 8). An additional step may be necessary to reference the position of the artifact with respect to the machine or part coordinates.

4.8 *AM Process Monitoring Modalities*—In the context of this guide, *modality* describes a group of similar process monitoring technologies, grouped based on similar attributes regarding the measured object(s) or phenomena of interest, or the types of measurement instruments employed. In-depth discussion of different modalities are discussed beginning in Section 7. Different modalities may be sub-categorized or grouped in different ways. An additional important descriptor for process monitoring techniques is the *physical configuration* of the sensor(s).

4.8.1 *Physical Configurations*—Process monitoring sensors of various types can be fixed to stationary locations onto or within the AM machine. The same type of sensor can be fixed into different configurations, which will change the position, field of view, or coordinate frame in which the sensor data is defined. The two primary configurations used in LPBF in-process monitoring, *staring configuration*, and *co-axial configuration*, are shown in Fig. 7.

4.8.1.1 *Staring Configuration,* also known as 'offline' or 'fixed position' configuration. This is a non-contact configuration where the sensor is placed in a fixed position with respect to the build plane or machine coordinate system (see ISO/ASTM 52921). A staring configuration sensor can be fixed either inside or outside the controlled-environment (build) chamber. This configuration is typical with single-point pyrometer, camera or thermal imager, etc.

4.8.1.2 *Co-axial Configuration,* also known as 'on-axis' or 'inline'. This is a non-contact configuration especially suited for optical or radiometric sensors, where the sensor is mounted in an optical path shared by the laser heat source. The field of view of the sensor is then fixed to the moving reference frame of the laser spot and moves in the same scan trajectories of the laser throughout the fabrication process. This effectively keeps the melt pool stationary within the sensor field of view. Example sensors include filtered radiometers, spectrometers, or high-speed cameras.

4.8.1.3 *Other Configurations*—A variety of other physical instrument configurations can exist that may be unique, specialized, or not easily described by the aforementioned configurations. For example, an acoustic microphone may be suspended within the build chamber, or an oxygen sensor set within the inert gas recirculation system (for example, machine condition monitoring, Section 9).

5. Basis of Application

5.1 Rationale for application of AM in-process monitoring is varied, and depends on the products being developed and their qualification or certification requirements (see 4.1 production versus development and 4.5 on Economic Justification).

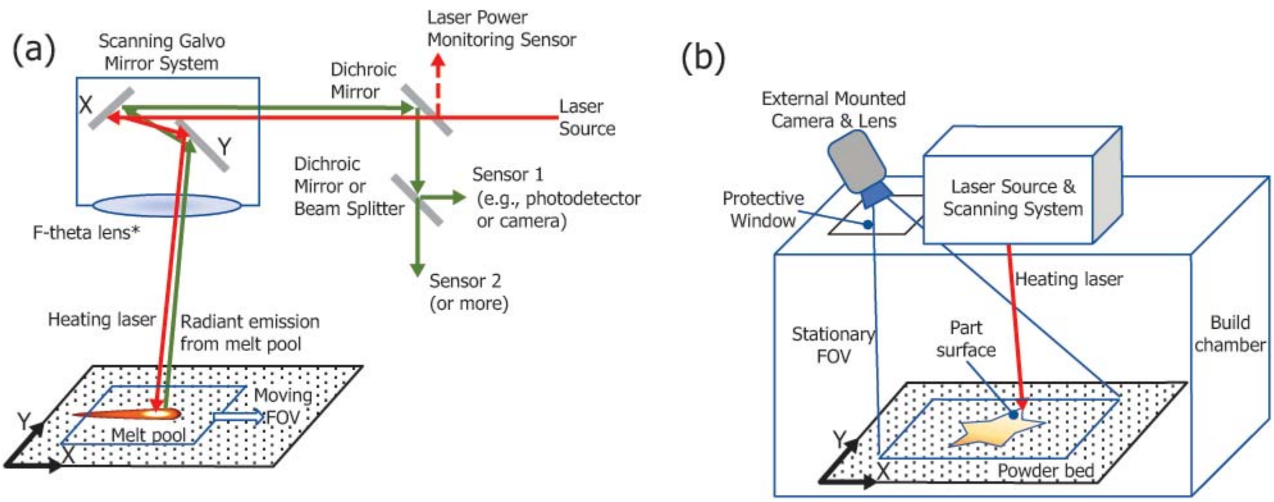


FIG. 7 Example Schematic of Two Common Instrument Physical Configurations in Laser Powder Bed Fusion (LPBF) Process Monitoring: (a) Co-axial Configuration and (b) Staring Configuration

5.2 *Flaw Detection*—A primary intended use for AM process monitoring is to identify the formation or existence of flaws during the fabrication process, so that it may supplement (or possibly replace) ex-situ part quality measurements. This may be used to direct or inform location-specific post-build NDE, form the basis for accept/reject criteria, or provide supplemental characterization of the build process or part design. For an AM flaw catalog and a review of relevant post-process NDT standards under ISO jurisdiction, refer to ISO/ASTM TR 52905. A list and review of technically relevant flaws that are exhibited in the final part and potentially observed through ex-situ NDT methods are provided in Guide E3166. Also, refer to subcommittee ASTM F42.01 for proposed standards on test methods for intentionally seeding flaws. In addition to these ex-situ observed flaws, those exhibited in-process are discussed in context of the different measurement modalities beginning in Section 7.

5.2.1 *Probability of Detection (POD)*—The concept of POD analysis may be applied to in-process monitoring, but specific examples are limited at the time of publication of this guide. Readers may want to refer to published standards from ASTM E07.10 on Specialized NDT Methods regarding POD analysis (for example, Practice E2862, Practice E3023).

5.3 *Statistical Process Control (SPC)*—Statistical process control (SPC) is defined as the application of statistical techniques to control a process. This control is achieved by taking action on the partitioning of process variation into *common cause variation* and *special cause variation*. Common cause variation results from the natural variability of the process or “stochastic noise.” Special cause variation results from deviations that, with appropriate diligence, can be attributed to a specific reason. A key concept of SPC is to promptly identify when the process is *out-of-control* due to the onset of special cause variation so that timely corrective action can be taken, and not tampering with the background noise of the process resulting from common cause variation. The long-term goal is to continually reduce the common cause variation through systemic improvements. The term SPC will be used to include control charts, control limits, specification or tolerance limits, process capability, out of control action plan systems, and matching/equivalency testing. Reference Practice E2587.

5.3.1 *Terms:*

5.3.1.1 *Control Chart* is a trend chart of a measurement or a statistic in time order with control limits and a centerline which define ‘usual’ process performance. A control chart is intended to model, partition and monitor the process variation into Common Cause and Special Cause (see Fig. 8).

(1) Control Limits and Centerlines define the partitions of Common Cause and Special Cause variation, and are established from a reference data set. This reference data set is assumed to be devoid of any Special Cause variation. Control limits are estimated from this reference data, usually calculated as the process mean plus and minus three standard deviations. All subsequent data are plotted on the control chart and compared to the control limits. Observations beyond the control limits are indicative of out-of-control state caused due to Special Cause variation.

(2) SPC Challenges in AM Process Monitoring—Identifying and formulating the appropriate control variables and control statistics are one of the challenges with SPC of AM in-process measurements. It is undoubtedly preferable for the measurements to have strong causal relationships to final product quality, but the relative juvenescence of the industry makes many of these relationships unproven, and only estimated from other tangentially-but-incompletely-related technologies, like welding and materials science. If every possible metric is subjected to rigorous SPC, data overload can hamper analysis and improvement efforts. Over time, use continuous improvement methods to drive for SPC procedures that elegantly partition variation with the appropriate amount of effort/overhead and directly relate to final product quality.

(3) Identifying and Defining Control Limits—Another particular challenge of the SPC of AM in-process measurements is one of the calculations of control limits for process subgroupings and summarizations where trends, steps, and discontinuities are natural components of Common Cause variation. Limits calculated classically will generally be inappropriate, being too loose or too tight. Control limits and centerlines

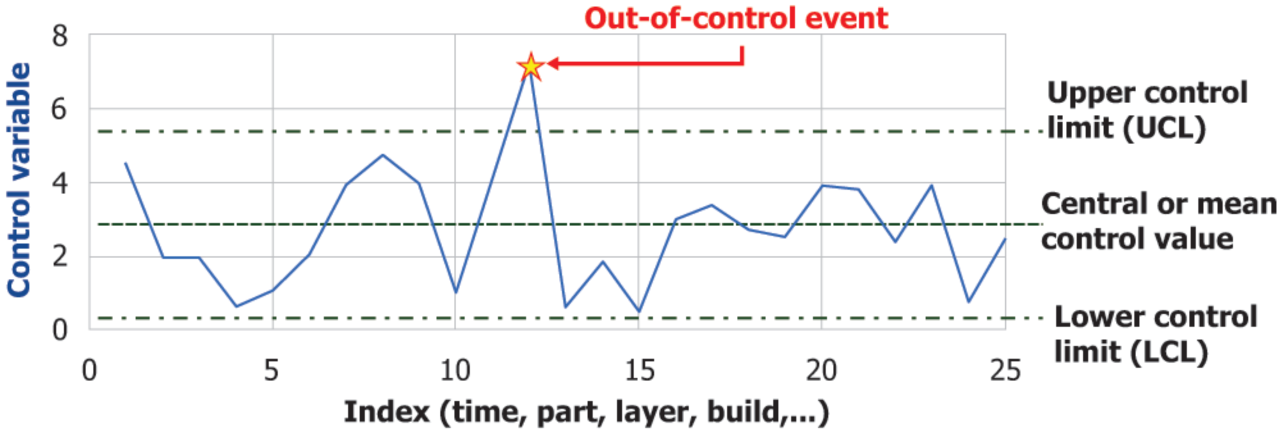


FIG. 8 Example of a Basic Control Chart

should be evaluated regularly for appropriateness to task. Loose control limits are too insensitive to detect Special Cause variation and miss true signals, a "false negative" or Type II error. Tight control limits are too sensitive to Common Cause variation, a "false positive" or Type I error that can encourage tampering, or signal many false alarms that can lead to the dangerous ignoring of all OOC signals (including the cessation of SPC). The success of SPC hinges upon limits that are calculated from documented procedures based on probability whose range is "just right," detecting Special Cause variation that needs to be eliminated and disregarding Common Cause variation. This topic remains an area of active research as of this writing.

5.4 *Machine Learning*—The main utility of machine learning is to identify patterns in data symptomatic of certain process states or outcomes. Machine learning (ML) is broadly researched for applications in AM process monitoring, and some ML applications are appearing in commercial AM process monitoring products. ML is particularly useful in the analysis of AM process monitoring due to three main aspects (colloquially, the *three V's*): (*1*) A *variety* of sensor types and modalities are used in process monitoring, often simultaneously, and certain ML techniques can provide improved or more sensitive response to a combination of data (for example, sensor fusion); (*2*) *volume* of AM process monitoring data is typically large (see 4.7.4), where many ML algorithms are designed to make use of and may have improved performance from increased volume of available data to construct or train the model or algorithm; and (*3*) *velocity* of AM process monitoring data (for example, sampling rate or data acquisition rate) can be high, stemming from the fact that many melt pool phenomena occur at microsecond scale (see 7.3.4). Many ML algorithms or models, once created, can be extremely computationally efficient or make use of efficient computing hardware (for example, graphical processing units), which can enable real-time data processing at the same rate the process monitoring data is acquired.

5.4.1 *Ground Truth Data*—In assessing these algorithms, it is important to have so-called ground truth data that is obtained via materials characterization and testing, for example, XCT and microscopy.

5.4.2 *Volume of Data*—Proper development of predictive ML models require sufficient number of measurement and ground-truth pairs of data. The volume must be sufficient to produce three categories of ML model construction: *training, testing*, and *validation*. The ML algorithm is *trained* or modeled from the training data set. Next, the viability of the model is ascertained and checked with the testing data set to ensure that the model is adequate, in that it does not underfit or overfit the data, or have systemic bias. Lastly, the validation data set is used as a final check, and on which the model performance is reported. The data must be segregated into these three categories even *before* any machine learning model is considered. A typical classification is the 70-20-10 scheme, where 70 % of the data is used for training, 20 % for testing, and 10 % for validation. It is critical to ensure that the data are not shuffled or intermixed at any time. All results must be reported, if different machine learning algorithms are compared, on the validation data. It is recommended that the validation process be carried out in a double-blind or single-blind manner. No changes are allowed to the model based on results from the validation data set, but changes are allowed to the model after evaluation on the testing data set.

5.5 *Consideration of Self-healing and False Positive Indication*—Typical build parameters in LPBF require that lower layers and adjacent scan tracks be sufficiently re-melted by the active melt pool in order to create fully dense final parts without pores, voids, or cracks. A defect or flaw that occurs momentarily during the fabrication, and which elicits some process signature measured by an in-process monitoring sensor, may then be re-melted and not be present in the final part. If a model or correlation is made based on ex-situ measured part defects (ground truth) to correlate or identify associated in-process signatures, this model will inherently result in false positives. In other words, when a monitoring system or sensor indicates a defect has formed, there is a probability that the defect will be re-melted, and not exhibit in the final part. This effect is well known, although quantification, such as formation of a *probability of self-healing* (distinguishable from probability of detection), is still undergoing research.