Designation: E3166 – 20

Standard Guide for Nondestructive Examination of Metal Additively Manufactured Aerospace Parts After Build[1]

This standard is issued under the fixed designation E3166; 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 discusses the use of established and emerging nondestructive testing (NDT) procedures used to inspect metal parts made by additive manufacturing (AM).

1.2 The NDT procedures covered produce data related to and affected by microstructure, part geometry, part complexity, surface finish, and the different AM processes used.

1.3 The parts tested by the procedures covered in this guide are used in aerospace applications; therefore, the inspection requirements for discontinuities and inspection points in general 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 The manufacturing processes considered use powder and wire feedstock, and laser or electron energy sources. Specific powder bed fusion (PBF) and directed energy deposition (DED) processes are discussed.

1.6 This guide discusses NDT of parts after they have been fabricated. Parts will exist in one of three possible states: *(1)* raw, as-built parts before post-processing (heat treating, hot isostatic pressing, machining, etc.), *(2)* intermediately machined parts, or *(3)* finished parts after all post-processing is completed.

1.7 The NDT procedures discussed in this guide are used by cognizant engineering organizations to detect both surface and volumetric flaws in as-built (raw) and post-processed (finished) parts.

1.8 The NDT procedures discussed in this guide are computed tomography (CT, Section 7, including microfocus CT), eddy current testing (ET, Section 8), optical metrology (MET, Section 9), penetrant testing (PT, Section 10), process compensated resonance testing (PCRT, Section 11), radiographic testing (RT, Section 12), infrared thermography (IRT, Section 13), and ultrasonic testing (UT, Section 14). Other NDT procedures such as leak testing (LT) and magnetic particle testing (MT), which have known utility for inspection of AM parts, are not covered in this guide.

1.9 Practices and guidance for in-process monitoring during the build, including guidance on sensor selection and in-process quality assurance, are not covered in this guide.

1.10 This guide is based largely on established procedures under the jurisdiction of ASTM Committee E07 on Nondestructive Testing and is the direct responsibility of the appropriate subcommittee therein.

1.11 This guide does not recommend a specific course of action for application of NDT to AM parts. It is intended to increase the awareness of established NDT procedures from the NDT perspective.

1.12 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.

1.13 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.

1.14 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.

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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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1.15 *Units*—The values stated in SI units are to be regarded as standard. The values given in parentheses after SI units are provided for information only and are not considered standard.

1.16 *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.*

1.17 *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.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

E11 Specification for Woven Wire Test Sieve Cloth and Test Sieves

E94/E94M Guide for Radiographic Examination Using Industrial Radiographic Film

E114 Practice for Ultrasonic Pulse-Echo Straight-Beam Contact Testing

E215 Practice for Standardizing Equipment and Electromagnetic Examination of Seamless Aluminum-Alloy Tube

E243 Practice for Electromagnetic (Eddy Current) Examination of Copper and Copper-Alloy Tubes

E317 Practice for Evaluating Performance Characteristics of Ultrasonic Pulse-Echo Testing Instruments and Systems without the Use of Electronic Measurement Instruments

E426 Practice for Electromagnetic (Eddy Current) Examination of Seamless and Welded Tubular Products, Titanium, Austenitic Stainless Steel and Similar Alloys

E494 Practice for Measuring Ultrasonic Velocity in Materials

E543 Specification for Agencies Performing Nondestructive Testing

E571 Practice for Electromagnetic (Eddy-Current) Examination of Nickel and Nickel Alloy Tubular Products

E587 Practice for Ultrasonic Angle-Beam Contact Testing

E664/E664M Practice for the Measurement of the Apparent Attenuation of Longitudinal Ultrasonic Waves by Immersion Method

E747 Practice for Design, Manufacture and Material Grouping Classification of Wire Image Quality Indicators (IQI) Used for Radiology

E797/E797M Practice for Measuring Thickness by Manual Ultrasonic Pulse-Echo Contact Method

E1001 Practice for Detection and Evaluation of Discontinuities by the Immersed Pulse-Echo Ultrasonic Method Using Longitudinal Waves

E1004 Test Method for Determining Electrical Conductivity Using the Electromagnetic (Eddy Current) Method

E1025 Practice for Design, Manufacture, and Material Grouping Classification of Hole-Type Image Quality Indicators (IQI) Used for Radiography

E1030 Practice for Radiographic Examination of Metallic Castings

E1032 Practice for Radiographic Examination of Weldments Using Industrial X-Ray Film

E1158 Guide for Material Selection and Fabrication of Reference Blocks for the Pulsed Longitudinal Wave Ultrasonic Testing of Metal and Metal Alloy Production Material (Withdrawn 2019)[3]

E1065 Practice for Evaluating Characteristics of Ultrasonic Search Units

E1209 Practice for Fluorescent Liquid Penetrant Testing Using the Water-Washable Process

E1255 Practice for Radioscopy

E1316 Terminology for Nondestructive Examinations

E1416 Practice for Radioscopic Examination of Weldments

E1417 Practice for Liquid Penetrant Testing

E1441 Guide for Computed Tomography (CT)

E1475 Guide for Data Fields for Computerized Transfer of Digital Radiological Examination Data

E1570 Practice for Fan Beam Computed Tomographic (CT) Examination

E1695 Test Method for Measurement of Computed Tomography (CT) System Performance

E1742 Practice for Radiographic Examination

E1817 Practice for Controlling Quality of Radiological Examination by Using Representative Quality Indicators (RQIs)

E1901 Guide for Detection and Evaluation of Discontinuities by Contact Pulse-Echo Straight-Beam Ultrasonic Methods

E1935 Test Method for Calibrating and Measuring CT Density

E2001 Guide for Resonant Ultrasound Spectroscopy for Defect Detection in Both Metallic and Non-metallic Parts

E2007 Guide for Computed Radiography

E2033 Practice for Radiographic Examination Using Computed Radiography (Photostimulable Luminescence Method)

E2104 Practice for Radiographic Examination of Advanced Aero and Turbine Materials and Components

E2338 Practice for Characterization of Coatings Using Conformable Eddy Current Sensors without Coating Reference Standards

E2339 Practice for Digital Imaging and Communication in Nondestructive Evaluation (DICONDE)

E2373/E2373M Practice for Use of the Ultrasonic Time of Flight Diffraction (TOFD) Technique

E2375 Practice for Ultrasonic Testing of Wrought Products

E2445 Practice for Performance Evaluation and Long-Term Stability of Computed Radiography Systems

E2446 Practice for Manufacturing Characterization of Computed Radiography Systems

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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] The last approved version of this historical standard is referenced on www.astm.org.

E2491 Guide for Evaluating Performance Characteristics of Phased-Array Ultrasonic Testing Instruments and Systems

E2534 Practice for Process Compensated Resonance Testing Via Swept Sine Input for Metallic and Non-Metallic Parts

E2597 Practice for Manufacturing Characterization of Digital Detector Arrays

E2698 Practice for Radiographic Examination Using Digital Detector Arrays

E2736 Guide for Digital Detector Array Radiography

E2737 Practice for Digital Detector Array Performance Evaluation and Long-Term Stability

E2767 Practice for Digital Imaging and Communication in Nondestructive Evaluation (DICONDE) for X-ray Computed Tomography (CT) Test Methods

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

E2884 Guide for Eddy Current Testing of Electrically Conducting Materials Using Conformable Sensor Arrays

E2982 Guide for Nondestructive Testing of Thin-Walled Metallic Liners in Filament-Wound Pressure Vessels Used in Aerospace Applications

E3022 Practice for Measurement of Emission Characteristics and Requirements for LED UV-A Lamps Used in Fluorescent Penetrant and Magnetic Particle Testing

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

E3081 Practice for Outlier Screening Using Process Compensated Resonance Testing via Swept Sine Input for Metallic and Non-Metallic Parts

F2971 Practice for Reporting Data for Test Specimens Prepared by Additive Manufacturing

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

F3187 Guide for Directed Energy Deposition of Metals

ISO/ASTM 52900 Terminology for Additive Manufacturing Technologies

ISO/ASTM DTR 52905 Additive Manufacturing—General Principles—Non-destructive Testing of Additive Manufactured Products

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

2.2 *AIA Standard:*[4]

NAS 410 NAS Certification & Qualification of Nondestructive Test Personnel, Revision 4, 2014

2.3 *ANSI Standard:*[5]

ANSI, Z136.1-2000 American National Standard for Safe Use of Lasers

2.4 *ASNT Standard and Practice:*[6]

ASNT CP-189 Standard for Qualification and Certification of Nondestructive Testing Personnel

SNT-TC-1A Recommended Practice for Nondestructive Testing Personnel Qualification and Certification

2.5 *AWS Standard:*[7]

AWS D17.1 Specification for Fusion Welding of Aerospace Application

2.6 *EN Documents:*[8]

EN 4179 Aerospace Series—Qualification and Approval of Personnel for Non-Destructive Testing

EN 15708-2 Non Destructive Testing—Radiation Methods—Computed Tomography—Part 2: Principle, Equipment and Samples

EN 15708-3 Non Destructive Testing—Radiation Methods—Computed Tomography—Part 3: Operation and Interpretation

EN 15708-4 Non Destructive Testing—Radiation Methods—Computed Tomography—Part 4: Qualification

EN 60825-1 Safety of Laser Products. Equipment Classification and Requirements

2.7 *Federal Standards:*[9]

10 CFR 20 Standards for Protection Against Radiation

21 CFR 1020.40 Cabinet X-ray Systems

21 CFR 1040.10 Laser Products

21 CFR 1040.11 Specific Purpose Laser Products

29 CFR 1910.1096 Occupational Safety and Health Standards

2.8 *ISO Standard:*[10]

ISO 17296-2 Additive Manufacturing—General Principles—Part 2: Overview of Process Categories and Feedstock

2.9 *MIL Documents:*[11]

MIL-HDBK-1823 Nondestructive Evaluation System Reliability Assessment

MIL-STD-1907 Inspection, Liquid Penetrant and Magnetic Particle, Soundness Requirements for Materials, Parts, and Weldments

2.10 *NASA Standards:*[12]

NASA-STD-5009 NASA Technical Standard, Nondestructive Evaluation Requirements for Fracture Critical Metallic Components

MSFC-STD-3716 Standard for Additively Manufactured Spaceflight Hardware by Laser Powder Bed Fusion in Metal

MSFC-SPEC-3717 Specification for Control and Qualification of Laser Powder Bed Fusion Metallurgical Processes

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[4] Available from Aerospace Industries Association (AIA), 1000 Wilson Blvd., Suite 1700, Arlington, VA 22209, http://www.aia-aerospace.org.

[5] Available from American National Standards Institute (ANSI), 25 W. 43rd St., 4th Floor, New York, NY 10036, http://www.ansi.org.

[6] Available from American Society for Nondestructive Testing (ASNT), P.O. Box 28518, 1711 Arlingate Ln., Columbus, OH 43228-0518, http://www.asnt.org.

[7] Available from American Welding Society (AWS), 8669 NW 36 St., #130, Miami, FL 33166-6672, http://pubs.aws.org/.

[8] Available from British Standards Institution (BSI), 389 Chiswick High Rd., London W4 4AL, U.K., http://www.bsigroup.com.

[9] Published by the Center for Devices and Radiological Health (CDRH) of the Food and Drug Administration (FDA); available from Government Printing Office Superintendent of Documents, 732 N. Capitol St., NW, Mail Stop: SDE, Washington, DC 20401.

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

[11] Available from Standardization Documents Order Desk, Bldg 4 Section D, 700 Robbins Ave., Philadelphia, PA 19111-5094, Attn: NPODS.

[12] Available from the NASA Technical Standards System at the NASA website, www.standards.nasa.gov.

2.11 *NBS Handbook:*[13]

114 General Safety Standard for Installations Using Non-Medical X-ray and Sealed GammaRay Sources, Energies up to 10 MeV

2.12 *SAE Standards:*[14]

AMS 2644 Inspection Material, Penetrant

AMS 2175 Castings, Classification and Inspection of

2.13 *USAF Document:*[15]

AFRL-RX-WP-TR-2014-0162 America Makes: National Additive Manufacturing Innovation Institute (NAMII) Project 1: Nondestructive Evaluation (NDE) of Complex Metallic Additive Manufactured (AM) Structures

2.14 *VDI Document:*[16]

VDI/VDE 2630 Various Parts, Computed Tomography in Dimensional Measurement—Fundamentals and Definitions

3. Terminology

3.1 *Abbreviations*—The following abbreviations are adopted in this guide: Computed Tomography (CT), Eddy Current Testing (ET), Optical Metrology (MET), Penetrant Testing (PT), Process Compensated Resonance Testing (PCRT), Radiographic Testing (RT), Infrared Thermography (IRT), and Ultrasonic Testing (UT).

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

3.2.1 For terminology related to NDT, use Terminology E1316.

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

3.2.3 For terminology related to powder metallurgy, including powder, powder types, powder additives, powder evaluation procedures and powder processing techniques, use Practice E243.

3.3 *Definitions:*

3.3.1 *cognizant engineering organization, n*—see Terminology E1316.

3.3.2 *defect, n*—see Terminology E1316.

3.3.2.1 *Discussion*—Defects do not meet specified acceptance criteria and are rejectable.

3.3.3 *discontinuity, n*—see Terminology E1316.

3.3.4 *flaw, n*—see Terminology E1316.

3.3.4.1 *Discussion*—Types of flaws (not necessarily rejectable) specific to additive manufacturing include porosity/voids (isolated or cluster, surface or deeply embedded), lack of fusion, layer discontinuities (planar or linear), across-layer discontinuities, start-stop errors, inclusions, layer shifts, under/over-melted material, metastable microstructures, residual stress, and poor dimensional accuracy.

3.4 *Definitions of Terms Specific to This Standard:*

3.4.1 *as-built, adj*—refers to the state of the manufactured part before any post-processing, except where removal from a base plate is necessary, or powder removal or support removal is required.

3.4.2 *aspect ratio, n*—the diameter to depth ratio of a flaw.

3.4.2.1 *Discussion*—For irregularly shaped flaws, diameter refers to the minor axis of an equivalent rectangle that approximates the flaw shape and area.

3.4.3 *crack, n*—separation of material which may be intergranular or transgranular in metals; in severe cases, it can result in 2-D (planar) separation (delamination) between adjacent build layers.

3.4.3.1 *Discussion*—Cracks are caused by temperature differences during melting or sintering, or relief of residual stresses upon cooling, and can be manifested at the microscopic level (hot tears) to macroscopic level (delamination).

3.4.4 *directed energy deposition (DED), n*—an additive manufacturing process in which focused thermal energy is used to fuse materials by melting as they are being deposited.

3.4.4.1 *Discussion*—"Focused thermal energy" means that an energy source (for example, laser, electron beam, or plasma arc) is focused to melt the materials being deposited.

3.4.5 *hit, n*—an existing discontinuity that is detected as a find during NDT.

3.4.6 *inclusion, n*—foreign material, either non-metallic or metallic, incorporated into the deposited material.

3.4.6.1 *Discussion*—Inclusions are typically oxides, nitrides, hydrides, carbides, or a combination thereof and may or may not have some coherency with the surrounding material.

3.4.7 *lack of fusion (LOF), n*—a type of process-induced porosity, in which the powder or wire feedstock is not fully melted or fused onto the previously deposited substrate.

3.4.7.1 *Discussion*—In PBF, this type of flaw can be an empty cavity, or contain unmelted or partially fused powder, referred to as unconsolidated powder. LOF typically occurs in the bulk, making its detection difficult. Like voids, LOF can occur across single (horizontal LOF) or multiple layers (vertical LOF).

3.4.8 *miss, n*—an existing discontinuity that is not detected during NDT, whether due to the inspection system or human factors.

3.4.9 *near net shape, n*—condition where the parts require little post-processing to meet dimensional tolerance.

3.4.10 *poor dimensional accuracy, n*—physical measurements of geometrical features that do not meet engineering drawing, leading to an out-of-tolerance part.

3.4.10.1 *Discussion*—This type of flaw is caused by stair stepping, relief of residual stresses and associated warping, rapid contraction during cooling after fusion, or sagging under

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[13] Available from the United States Department of Commerce, National Bureau of Standards.

[14] Available from SAE International (SAE), 400 Commonwealth Dr., Warrendale, PA 15096, http://www.sae.org.

[15] Available from Air Force Research Laboratory, Materials and Manufacturing Directorate, Wright-Patterson Air Force Base, OH 45433-7750 (Air Force Materiel Command, United States Air Force).

[16] Available from Verein Deutscher Ingenieure (VDI), Postfach 1139, Dusseldorf 1, Germany 4000.

gravity of unsupported areas with vertical overhang or downward facing surfaces during build.

3.4.11 *porosity, n*—see ISO/ASTM Terminology 52900.

3.4.12 *porosity (gas), n*—voids that are spherical or faceted in shape; with sufficient sources of gaseous species, may be intermittent within the deposit or elongated, interconnected, or chained due to the moving solidification front.

3.4.12.1 *Discussion*—Gas porosity is caused by absorption/desorption of gaseous species (nitrogen, oxygen) during solidification, or volatile contaminants (moisture or hydrocarbons) in the feedstock. Gas porosity on the surface can interfere with or preclude certain NDT methods, while porosity inside the part can reduce strength in its vicinity. Like voids, gas porosity causes a part to be less than fully dense.

3.4.13 *porosity (keyhole), n*—a type of porosity characterized by a circular depression formed due to instability of the vapor cavity during processing.

3.4.13.1 *Discussion*—Keyhole porosity is created when the 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.

3.4.14 *powder bed fusion (PBF), n*—an additive manufacturing process in which thermal energy selectively fuses (melts or sinters) regions of a powder bed.

3.4.15 *probability of detection (POD), n*—the fraction of nominal discontinuity sizes expected to be found given their existence.

3.4.16 *soak time, n*—the period during which a thermal image is acquired beginning with the introduction of a gas or liquid into the additively manufactured part.

3.4.17 *thermal conductivity, n*—the time rate of steady heat flow through the thickness of an infinite slab of a homogeneous material perpendicular to the surface, induced by unit temperature difference.

3.4.17.1 *Discussion*—The property should be identified with a specific mean temperature, since it varies with temperature.

3.4.18 *thermal diffusivity, n*—the ratio of thermal conductivity to the product of density and specific heat; a measure of the rate at which heat propagates in a material; units [length^2 time^{-1}].

3.4.19 *thermal discontinuity, n*—a change in the thermophysical properties of a specimen that disrupts the diffusion of heat.

3.4.20 *voids, n*—a general term encompassing both irregularly-shaped or elongated cavities (process-induced porosity, LOF, skipped layers, large cracks, or delamination) and spherically-shaped cavities (gas-induced and keyhole porosity).

3.4.20.1 *Discussion*—In PBF, these cavities can be empty or filled with partially or wholly unfused powder. Voids are distinct from intentionally added open cells that reduce weight. Voids cause a part to be less than fully dense.

3.5 *Symbols:*

3.5.1 *a*—the physical dimension of a discontinuity, flaw, or target—can be its depth, surface length, or diameter of a circular discontinuity, or radius of semi-circular or corner crack having the same cross-sectional area.

3.5.2 $a_{p/c}$—the discontinuity size that can be detected with probability *p* with a statistical confidence level of *c*.

4. Significance and Use

4.1 Metal parts made by additive manufacturing differ from their traditional metal counterparts made by forging, casting, or welding. Additive manufacturing produces layers melted or sintered on top of each other. The part's shape is controlled by a computer as well as by the layers. The computer directs energy from a laser or electron beam onto a powder bed or wire input material. These processing approaches have the potential of creating flaws that are undesirable in the as-built or finished part. In general, processing parameter anomalies and disruptions during a build may induce such "flaws." Flaws can also be introduced because of contaminants present in the input material.

4.2 Established NDT procedures such as those given in ASTM E07 standards are the basis for the NDT procedures discussed in this guide. These NDT procedures are used to inspect production parts before or after post-processing or finishing operations, or after receipt of finished parts by the end user prior to installation. The NDT procedures described in this guide are based on procedures developed for conventionally manufactured cast, wrought, or welded production parts.

4.3 Application of the NDT procedures discussed in this guide is intended to reduce the likelihood of material or component failure, thus mitigating or eliminating the attendant risks associated with loss of function, and possibly, the loss of ground support personnel, crew, or mission.

4.4 *Input Materials*—The input materials covered in this guide consist of, but are not limited to, ones made from aluminum alloys, titanium alloys, nickel-based alloys, cobalt-chromium alloys, and stainless steels. Input materials are either powders or wire.

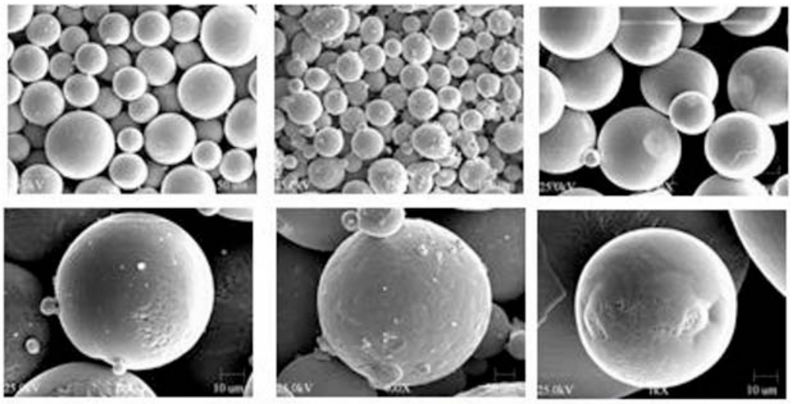
NOTE 3—When electron beams are used, the beam couples effectively with any electrically conductive material, including aluminum and copper-based alloys.

4.4.1 *Powders*—High-quality powders required for AM process are produced by *(1)* plasma atomization, *(2)* inert gas atomization, or *(3)* centrifugal atomization using rotating electrodes (Fig. 1).

4.4.1.1 One of the critical features of powders is the sieve size of the material. Metal powder is screened through wire test sieves as described in Specification E11. Section 5 and Table 1 in Specification E11 provide nominal dimensions and critical dimensions of the sieves.

4.4.1.2 Inclusions, if they exist within the raw powder, can be equal to the sieve size diameter, and by a rule of thumb have a ratio of length to diameter size of 4:1.

4.4.2 *Wire*—The diameter of the wire feedstock is the controlling factor determining the smallest detail attainable using this process: fine diameter wires may be used for adding fine details and large diameter wires to increase deposition rate



Wire Plasma Atomized

Gas Atomized

Plasma Rotating Electrode Process

FIG. 1 Three Different Powders of the Same Titanium Alloy

during bulk deposition. Wire-fed AM equipment (for example, EBF3 systems) can be fitted with two wire feeders that can be controlled simultaneously and independently. For example, two wire feeders may be loaded with either a fine and a coarse wire diameter for different feature definition or two different alloys to facilitate producing components with compositional gradients.

4.5 *Inspection Requirements*—The aerospace parts covered by this guide can be used in either fracture critical or non-fracture critical applications, for which the consequence of part failure may or may not be severe, or the design margin may or may not be low. These parts can either be high value assets manufactured in one-off or limited quantity production runs, such as the rocket engine baffle shown in Fig. 2, or they can be assets manufactured in higher volume production runs, such as turbine blades and LEAP engine fuel nozzles. In general, the NDT inspection requirements for these aerospace parts will be more stringent than for AM parts intended for general use. For additional guidance on determining the appropriate level of NDT relative to part category (for example, prototype parts, production parts, non-structural parts, primary structure fracture critical parts), refer to Section 5.

4.6 *Processes*—The AM processes covered in this guide are differentiated by input material (powder or wire), energy source (electron beam, laser beam, and plasma arc), and the degree of fusion (melting or sintering) (Fig. 3). Arc energy sources (typically GTA (gas tungsten arc), PA (plasma arc), PTA (plasma transferred arc), and GMA (gas metal arc)) used in DED are not discussed in this guide. For purposes of this guide, the AM processes are defined by ISO/ASTM 52900 and are subdivided into two additive manufacturing process categories: *(1)* PBF and *(2)* DED. For a discussion of the relative merits of the PBF and DED processes according to build volume, detail resolution, deposition rate, power efficiency, coupling efficiency, and cleanliness, consult Guide F3187. For details on DED feedstock, processing equipment (machine preparation, conditioning, calibration, and monitoring), atmospheric control, post-processing, safety, manufacturing plan, and process specification, also consult Guide F3187.

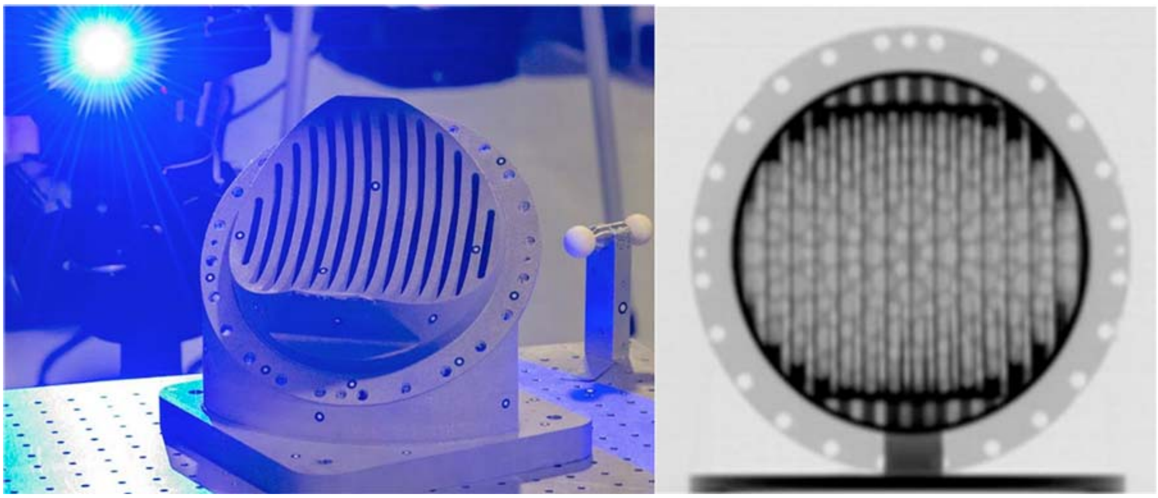


FIG. 2 Additively Manufactured Baffle for A Rocket Engine Built Using Selective Laser Melting and Inspected by Structured Light to Determine External Dimensions (Left) and Computed Tomography to Detect Internal Features (Right) (Courtesy of NASA Marshall Space Flight Center)

Type	Technologies
Powder Bed Fusion (powder)	Selective Laser Melting (SLM, laser cusing)
	Direct Metal Laser Sintering (DMLS)
	Selective Laser Sintering (SLS)
	Electron Beam Melting (EBM)
Directed Energy Deposition (powder or wire)	Electron Beam Additive Manufacturing, Electron Beam Freeform Fabrication (EBAM, EBF^3)
	Laser Material Deposition (LMD)
	Gas Tungsten Arc (GTA), Plasma Arc (PA), Plasma Transferred Arc (PTA), and Gas Metal Arc (GMA)

FIG. 3 Common Additive Manufacturing Processes for Metals

NOTE 4—Other AM processes, namely, vat photopolymerization, material jetting, binder jetting, material extrusion, and sheet lamination covered in ISO 17296-2, that rely on other energy sources such as a chemical reaction (for example, photopolymerization), or are specific to additive manufacturing of polymers and ceramics, are not considered in this guide.

4.6.1 *Powder Bed Fusion (PBF)*—In PBF systems, the energy source (electron beam or laser) is generally stationary, and is focused at a set deposition plane and the beam steered by optical or magnetic means. The feedstock in PBF systems is a powder that is fed from hoppers and screed to a uniform thickness at the beginning of each melt pass. After placement of the powder, the energy source is swept rapidly across the powder bed to melt and consolidate the current layer. Following consolidation, the build platform is indexed down by one layer thickness, and the process is repeated, building the part layer by layer (Fig. 4). Each PBF approach (Selective Laser Melting (SLM), Direct Metal Laser Sintering (DMLS), Selective Laser Sintering (SLS), and EBM (Electron Beam Melting)) has merits, and selection is based on the parts being fabricated. Both PBF and DED processes use Computer Aided Design (CAD) 3-D model data, which are prepared by "slicing" the model into build layers. Build volumes of the order of 64 L (40 × 40 × 40 cm) (4000 in.^{3} (~16 × 16 × 16 in.)) are possible.

NOTE 5—Selective Laser Melting (SLM) or Direct Metal Laser Sintering (DMLS) use a high power-density laser to melt and fuse metallic powders together. SLM is considered a subcategory of Selective Laser Sintering (SLS). The SLM or DMLS process has the ability to melt the

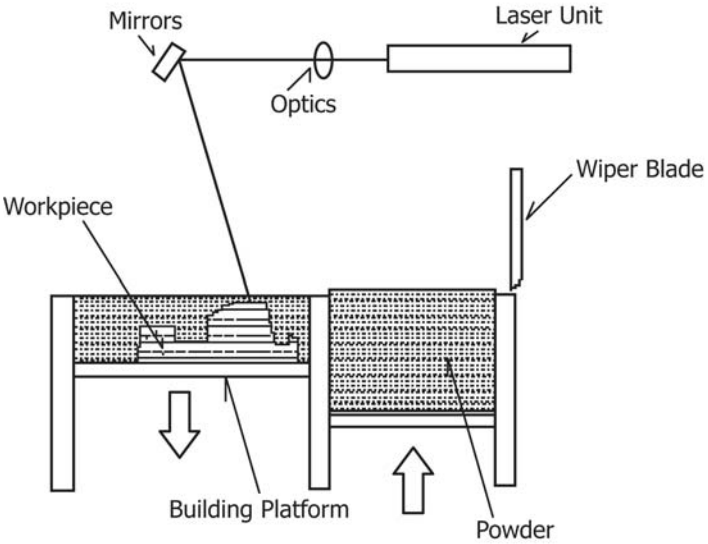


FIG. 4 Laser-beam Powder Bed Fusion

metal material fully to form a solid 3-D part, unlike SLS. SLS uses a laser to sinter powdered material (often a polymer, but ceramics and metals can also be used), producing different properties (crystal structure, porosity, etc.) than are produced in SLM or DMLS. SLS has mainly been used for rapid prototyping and for low-volume production of parts.

4.6.1.1 *Laser-Powder Bed Fusion (L-PBF)*—Lasers (for example, Nd-YAG) are used to fuse powders partially (sintering) or completely (melting). Sources of powder, specifically optimized for PBF, are available in a range of common engineering alloys while small lot sizes of specialty powder are becoming increasingly available. Variations in L-PBF equipment exist from vendor to vendor as well as in the proprietary procedures offered by each supplier to melt or sinter the metal into a formed part. Unique aspects of the PBF process (as compared with most conventional metal fabrication processes) include the rapid melting and cooling rate, a narrow melt pool, planar deposition, powder morphology, and the need for support structures. Surface conditions typically feature a layer of partially fused powder and irregularities such as stair stepping. The as-deposited material in the bulk displays banding and planar variations in microstructure and may include regions of unfused or partially fused powder. Post-processing procedures include heat treatment, hot isostatic pressing (HIP), machining, and surface finishing. The biggest challenge in the application of NDT to metal parts made by PBF processes is the flaw size (sub-micron to mm scale) and location (potentially everywhere).

(1) Selective Laser Melting (SLM)—A PBF process in which a high-energy laser selectively melts regions of thin layer of fine metal powder (powder bed) in the build chamber as directed by a computer. Since the input material is fully melted, an extremely dense, homogeneous, and strong part is produced with good surface quality and minimal porosity. The high temperature gradients that occur during the SLM process can also lead to stresses inside the final part, which can lead to part distortion. The chamber often is filled with argon or other inert shield gas to provide a non-contaminating atmosphere. The process starts by slicing 3-D CAD file data into layers, usually 20 to 100 microns (0.8 to 4 mils) thick, creating a 2-D image of each layer. SLM produces parts with dimensional accuracy and complex geometries; however, support structures are usually required during printing to reduce internal stress and distortion. Synonym: direct metal laser melting (DMLM).

NOTE 6—SLM is considered a subcategory of Selective Laser Sintering (SLS), but unlike SLS, the SLM process has the ability to melt the metal material fully to form a solid, homogeneous 3-D part.

NOTE 7—Laser cusing is a type of SLM process where each layer of the required cross section is divided into a number of segments called "islands," which are selected stochastically during scanning. This strategy ensures thermal equilibrium on the surface to reduce part stresses.

(2) Direct Metal Laser Sintering (DMLS)—The term 'DMLS' was originally introduced as a vendor-specific (EOS) product line analogous to SLM-based product lines. In both cases, fully dense, high strength parts with minimal porosity were produced. 'DMLS' used in this context, however, is a misnomer and arguably archaic, and is thus not preferred. In other (preferred) usage, DMLS denotes a process, in which a metal alloy is not heated enough to produce complete melting. This technique is especially useful for metal alloys versus pure metals, where partial melting is advantageous. DMLS is also known as Direct Metal Laser Melting (DMLM).

(3) Selective Laser Sintering (SLS)—A lower energy AM process, which involves partial melting of the input material. Like SLM, SLS produces parts with dimensional accuracy and complex geometries; however, support structures are generally not required. SLS parts are also less the fully dense, exhibiting surface and bulk porosity. SLS is mainly used for rapid prototyping and for low-volume production of parts. With SLS, it is possible to reduce shrinking and warping by heating the build chamber to a temperature just below that needed to sinter the powdered metal, polymer, or ceramic.

NOTE 8—SLS is used with a wider range of materials (metals, polymers, and ceramics) than DMLS (metals). The lower laser power produces different properties (crystal structure, porosity, etc.) than are produced by SLM.

4.6.2 *Electron Beam-Powder Bed Fusion (EB-PBF)*—Electron beam powder bed fusion (EB-PBF) is similar to L-PBF in many of the challenges presented to NDT examination. Differences with L-PBF include a smaller selection of powder alloys optimized for EB-PBF, a vacuum versus inert gas build chamber, different designs for support structures (used for heat conduction versus structural support), rougher surfaces, and larger melt pools. EB-PBF is typically performed at higher temperatures using an electron beam emitted by a heated tungsten filament, producing a deeper melt pool compared with L-PBF. Each powder bed layer is also scanned in two stages, the preheating stage and the melting stage. The larger melt pool results in poorer dimensional control and surface quality, but allows for high build rates and reduced residual stress. Preheating the powder bed layer on EB-PBF further reduces the thermal gradient between the powder bed and the scanned layer, which in turn reduces residual stresses in the part and the corresponding need for post-process heat treatment. The high vacuum (<10 mPa ($<10^{-4}$ torr)) chamber environment offers a high level of purity for reactive metals, thus reducing the production of flaws associated with contamination and pickup of oxygen, nitrogen, and other impurities. Post-processing removal of powder from internal volumes may be more challenging than with L-PBF. As with L-PBF, heat treatment, hot isostatic pressing, machining, and surface finishing may still be required to facilitate the successful application of NDT procedures.

4.6.2.1 *Electron Beam Melting (EBM)*—A free form EB-PBF fabrication method, which uses pre-alloyed powder, a heated fusion bed, an electron beam, and a high vacuum build chamber. This process creates full melting with the material characteristics of the target material. Build chambers are small with larger ones under development.

4.6.3 *Directed Energy Deposition (DED)*—In contrast to the layer-by-layer PBF screening and melt pass process, powder or wire feedstock for DED is delivered to the melt pool in coordination with a focused energy source and a shield gas or vacuum, and the deposition head (typically) indexes up from the build surface with each successive layer. DED systems are differentiated from PBF systems by the following general characteristics: ability to process large build volumes (up to 5000 L ($1.6 \times 1.6 \times 2.1$ m) (175 ft^3 ($5 \times 5 \times 7$ ft)) with minimal tooling and secondary processing, ability to produce parts with either composition gradients or hybrid structures consisting of multiple materials having different compositions and structures, ability to process at relatively high deposition rates, use for part repair and feature addition, and the use of articulated energy sources and feedstock delivered directly to the melt pool.

NOTE 9—Although DED systems can be used to apply a surface cladding, such use does not fit the current definition of additive manufacturing (AM). Cladding consists of applying a uniform buildup of material on a surface. To be considered AM, a CAD file of the build features is converted into section cuts representing each layer of material to be deposited. The DED machine then builds up material, layer-by-layer, so material is only applied where required to produce a part, add a feature, or make a repair.

4.6.3.1 *Laser DED With Powder*—Laser beam DED relies on laser melting of powder feed stock, including both powders used for L-PBF but also a wider range of alloy powders available for more common metal powder processing applications such as laser cladding. The process may be used to form entire parts or may be applied to an existing substrate or base component such as with refurbishment, remanufacturing, or hybrid (additive/subtractive) processing. Surface and subsurface conditions, flaws, and defects are similar to other PBF melted deposits and those of conventional laser welds. Defects may occur with the dissimilar combination of the base feature alloy, with the AM deposited alloy. The relatively small and distributed flaw size and surface condition may create challenges for direct application of existing NDT methods and the definition of allowable flaw sizes and locations.

4.6.3.2 *Electron Beam DED With Wire (DED-w)*—Electron beam DED is similar to electron beam welding in conduction mode melting (verses keyhole mode), featuring similar flaw morphology and evaluation using similar NDT methods. The process creates a large 3-D weld clad build-up to a near net shaped requiring post deposition machining and often heat treatments or hot isostatic pressing to achieve a final part. Unique aspects of the process include the high purity shield gas or vacuum environment of the chamber, the extended time at temperature of a build cycle, and the effect of as-deposited grain structure, alloy segregation, distortion, and residual stress. Operation in a vacuum ensures a clean process environment and eliminates the need for a consumable shield gas. Defects are similar to those found in inert gas arc welds and those associated with dissimilar combinations of the base feature alloy (for example, plate or shaft substrates) verses wire feedstock alloy. A wide range of weld wire alloys, certified for conventional weld processing, are available.

4.6.3.3 *Electron Beam Freeform Fabrication (EBF^3)*—This rapid direct metal deposition process can be used to build a complex, unitized part in a layer-additive fashion, although the more immediate benefit is for use as a manufacturing process for adding details to components fabricated from simplified castings and forgings or plate products. The EBF^3 process introduces metal wire feedstock into a molten pool that is created and sustained by a focused electron beam in a vacuum environment (10 mPa (10^{-4} torr) or lower). EBF^3 systems can be fixed or portable (Fig. 5) and consist of a high power electron beam gun and single or multiple wire feeders capable of independent or simultaneous operation. Other features of the EBF^3 process include:

(1) Programmable positioning using four (X, Y, Z, and rotation) to six axes of motion (X, Y, Z, gun tilt, positioner tilt, and rotate).

(2) Near 100 % efficient in feedstock consumption and approaches 95 % efficiency in power usage.

(3) Rapid bulk metal deposition rates in excess of 2500 cm^3/hr (150 in.^{3}/hr) as well as finer detail at lower deposition rates with the same equipment.

(4) Viable solutions to the issues of deposition rate, process efficiency, and material compatibility for insertion into the production environment.

4.6.3.4 *Laser DED with Wire (DED-w)*—This rapid direct metal deposition process can be used to build complex, unitized parts in a layer-additive fashion, or be used to add details to traditionally manufactured components. The laser DED-w process introduces metal wire feedstock into a molten pool that is sustained using a laser energy source (Fig. 6). Operation in an argon tent environment with oxygen levels low as 200 ppm ensures minimal oxidation and eliminates the need for a vacuum pump and chamber (Fig. 7). Systems can consist of multiple laser power sources or multiple wire feeders, or both, capable of independent or simultaneous operation. Deposition rates are scalable to laser power. For Ti-Al6-V4,

FIG. 5 Ground-based (Left) and Portable (Right) Electron-Beam Freeform Fabrication Systems (Courtesy of NASA Langley Research Center)

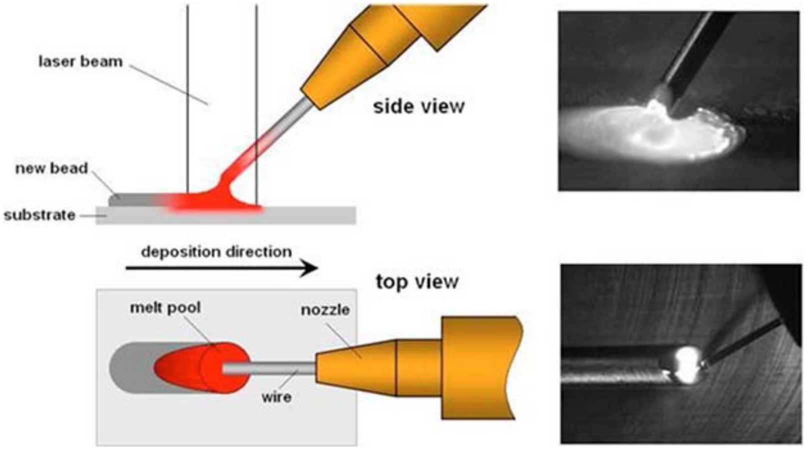


FIG. 6 Diagram of Laser Metal Deposition Process Using Wire Feedstock (Courtesy of GKN Aerospace)

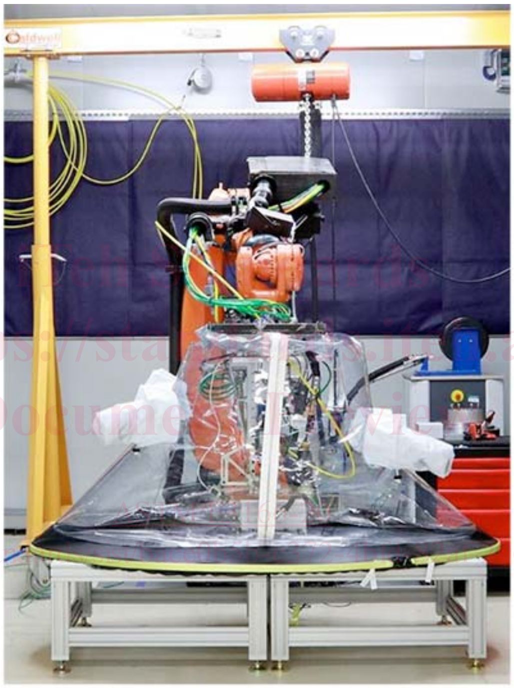


FIG. 7 Wire-fed Laser Metal Deposition Apparatus Using Inside of a Tent With an Argon Shield Gas (Courtesy of GKN Aerospace)

deposition rates approach 2 kg/hr per 10 kW of laser power. The process is nearly 100 % efficient in feedstock consumption.

4.7 *Post-Processing*—Stress relief, HIP, heat treatment, and polishing can affect the size and distribution of volumetric and surface flaws, and, therefore, the efficacy of the NDT method. Post-processing can also have a pronounced effect on part microstructure (Fig. 8). For this reason, parts should be consistently post-processed prior to NDT to ensure data reproducibility and repeatability.

NOTE 10—The closure of pores using HIP post-processing does not necessarily "heal" the flaw but may only close them. Fractography has shown the tearing of partially fused particle boundaries and closed pores in HIP-processed AM parts. An increase in part density may be achieved at the cost of masking the actual percentage of as-deposited porosity and its distribution. Work related to the effect of post-processing on mechanical properties such as fatigue response can be found elsewhere (2). The body of evidence regards substantial property improvement after HIP should be noted with this caution. The improvements from the HIP process are also reflected in reduced design factors. While as fabricated and post HIP may be warranted, it is well-established that current NDE is incapable to adjudicate soundness at the post HIP level.

NOTE 11—Post-processing can alter flaw size and distribution in a part, thus altering the probability of detection (POD) of a given flaw by NDT. For this reason, NDT before and after post-processing is recommended to determine if flaws are eliminated or introduced by post-processing, or to screen raw, as built parts before performing labor intensive post-processing steps.

4.8 *Flaws*—The occurrence of flaws in AM parts is governed by the particular material, processing, post-processing, and service history experienced by the part. The flaw types unique to the AM processes covered in this guide are still being identified and their effects on final properties determined. The

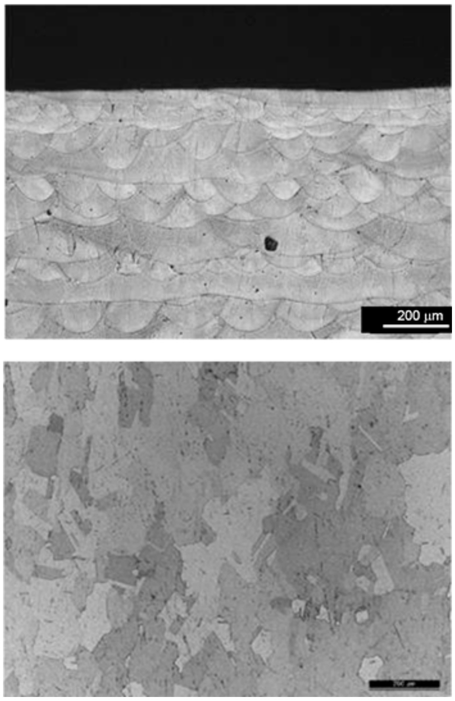


FIG. 8 Micrographs of As-build (Top) and Solution Aged/Heat-treated UNS N07718 Parts (Bottom) Showing Microstructures Dominated by the Characteristics of the Melt Pool (Top) Versus That of a Wrought Part Showing Expected Grain Size Variation (Bottom) (from Ref (1)).

flaw type for which the NDT capability is demonstrated is based on the level of understanding at the time of the part's design and the projected future screening importance. Metal parts fabricated by additive manufacturing can have cracks, porosity, LOF, trapped powder, inclusions, stop/start-type flaws, residual stress, and poor dimensional accuracy (Figs. 9-11). Parts can also have flaws introduced by post-processing, or damage caused by qualification testing before being placed into service. Once in service, additional damage can be incurred due to impact, cuts/scratches/abrasion, exposure to aerospace media, loading stresses, thermal cycling, physical aging, oxidation, and weathering. These factors will lead to complex damage states in the part that can be visible or invisible, macroscopic or microscopic. These damage states can be characterized by the presence of de-densification, depressions, chemical modification, microstructural variation, and foreign object debris (inclusions). Often these discontinuities can placed into four main categories: *(1)* manufacturing; *(2)* scratch/scuff/abrasion; *(3)* mechanical damage; and *(4)* cosmetic damage (no measureable effect on mechanical or end use properties). Although NDT can be used throughout a part's life cycle, its primary purpose is to detect flaws produced by manufacturing.

NOTE 12—NDT standard flaw classes for welds and castings (welding and casting defect quality standards) will generally not be applicable for AM parts.

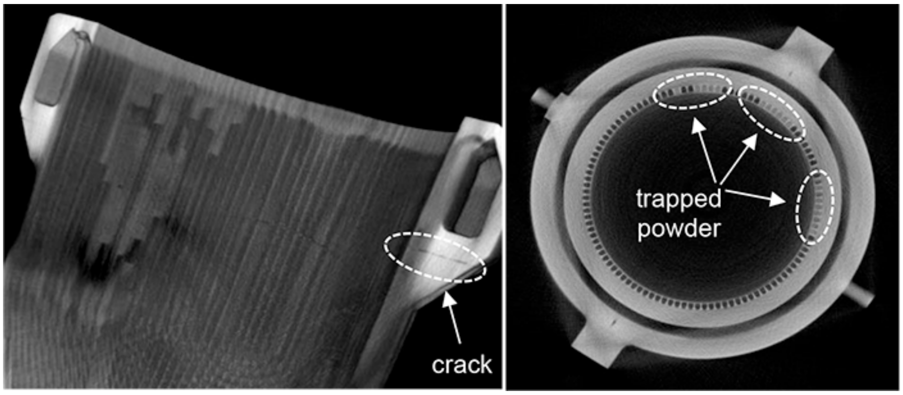


FIG. 9 Computed Tomograms Showing an Embedded Crack (Left) and Trapped Powder (Right) Inside on Cooling Channels in a Direct Metal Laser Sintered Copper Chamber (Courtesy of NASA Marshall Space Flight Center)

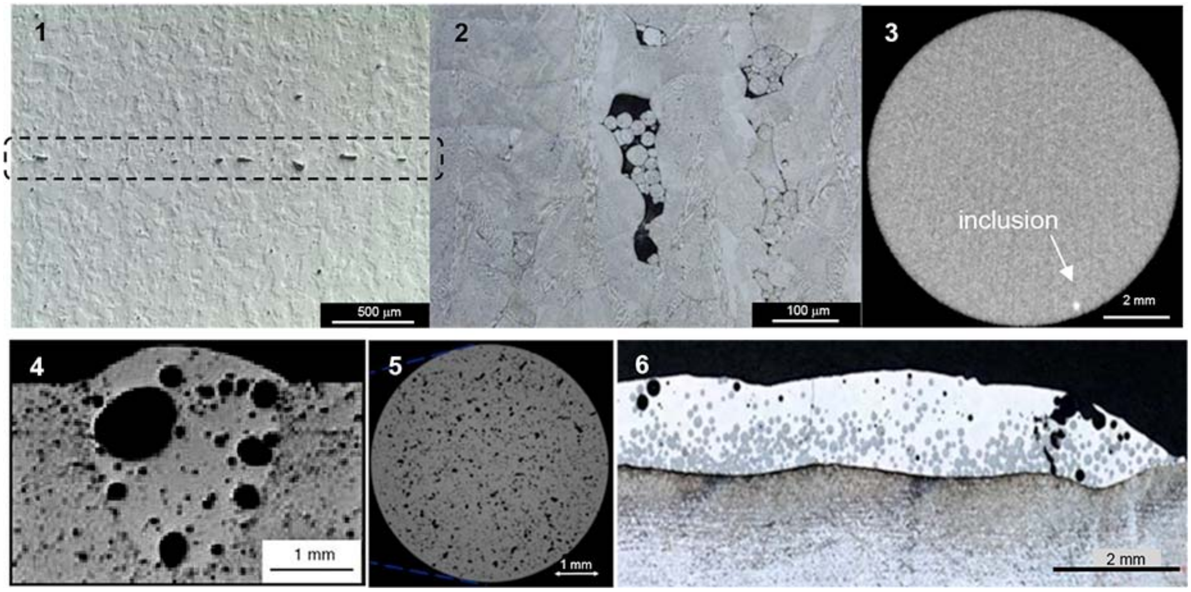


FIG. 10 Representative Additive Manufacturing Flaws: *(1)* **Layer Flaw (Micrograph),** *(2)* **Lack of Fusion (Micrograph),** *(3)* **Inclusion (Tomogram, Single Slice),** *(4)* **PBF Porosity (Micrograph),** *(5)* **Powder Bed Fusion Porosity (Volumetric Tomogram), and** *(6)* **Directed Energy Deposition Porosity (Micrograph) (Courtesy of the NASA Marshall Space Flight Center** *(1,3)***; Ana D. Brandão, Johannes Gumpinger, Michael Gschweitl, Christoph Seyfert, Peter Hofbauer, Tommaso Ghidini, Structural Integrity Procedia 7 (2017) 58-66, https://doi.org/10.1016/j.prostr.2017.11.061** *(5)***, and Manufacturing Technology Centre** *(2,4,6)***)**

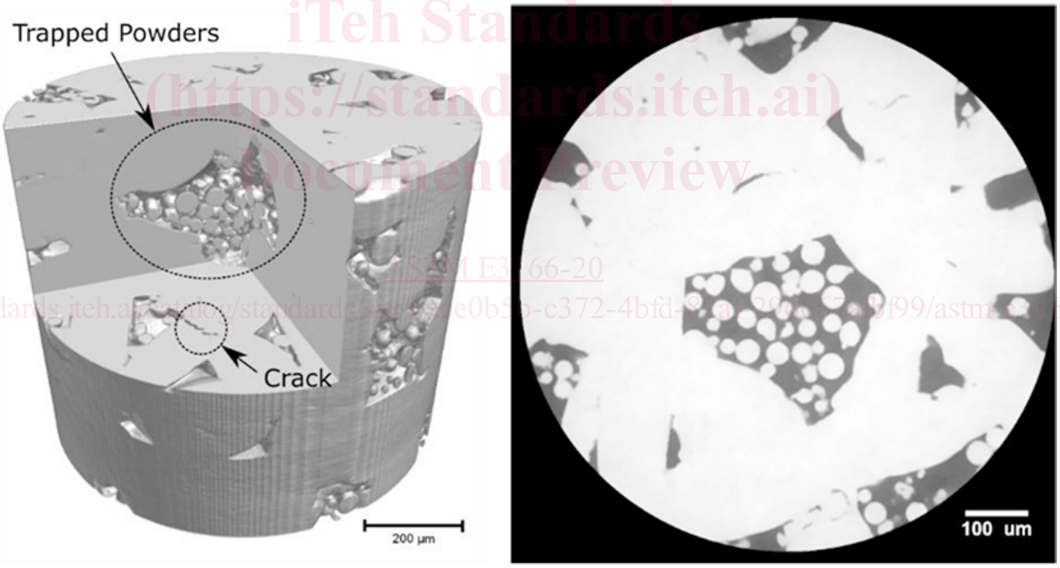


FIG. 11 Three-dimensional Rendering of the Computed Tomography Scan Obtained at About 0.9 µm⁄voxel Showing Unconsolidated Powder and a Crack (Left) and a Single Slice Tomogram of the Same Cobalt-chrome Laser-based Powder Bed Fusion Part (Right) (Courtesy of Kim FH, Moylan SP, Garboczi EJ, Slotwinski JA. Investigation of pore structure in cobalt chrome additively manufactured parts using X-ray computed tomography and three-dimensional image analysis. Additive Manufacturing. 2017;17:23-38.)

4.8.1 For an AM flaw catalog and a review of relevant post-process NDT standards under ISO jurisdiction, refer to ISO/ASTM DTR 52905.

4.8.2 Technologically important manufacturing flaws detected and characterized by NDT are:

4.8.2.1 *Porosity*—This type of flaw can be gas-induced or process-induced. In the former case, porosity is either created by a breach in the build container's atmosphere, or from trapped gas in the feedstock. In the latter case, porosity is created by unintended variation in the process parameters, for example, beam attenuation, resulting in under-melted material; or conversely, excessively high energy density of the beam, resulting in over-melting and hydrodynamic collapse of the melt pool (keyhole porosity). Regardless of origin, porosity is controlled in traditional metal casting processes by hot isostatic pressing (HIP). This process is generally effective, but current design requirements may call out for the detection of porosity (especially in regions of high design load). Large pores may not be completely healed (closed) and may be of interest for detection by NDT.

4.8.2.2 *Voids*—A general term encompassing both irregularly shaped or elongated cavities (process-induced porosity, LOF), spherically shaped cavities (gas-induced and keyhole porosity), cracks, and skipped layers. These cavities can be empty or filled with partially or wholly unfused powder. Voids are distinct from intentionally added open cells to reduce weight. Voids cause a part to be less than fully dense.

4.8.2.3 *Lack of Fusion/Unconsolidated Powder*—Created due to a local reduction in laser power, high scan speed, contamination, spatter, or other incorrectly adjusted process parameters, or a combination thereof, causing less than full densification of the part (Fig. 10, panel 2; and Fig. 11). In PBF, there are degrees to which the power can fluctuate, thus causing varying amounts of LOF as manifested by the presence of unconsolidated powder. In PBF, unconsolidated powder represents a unique additive manufacturing flaw type, and is not related to flaws occurring in welding processes where two members do not fuse. This type of flaw occurs in at least one layer or extends across multiple layers. When in a single layer (horizontal LOF), the volume of the part affected by this type of flaw can be significant. For example, for a build consisting of 0.75 mm (0.030 in.) layers, horizontal LOF in a single layer could represent 10 % of the volume of a 7.5 mm (0.300 in.) thick build. When this type of flaw extends across multiple layers (vertical LOF), it typically occurs at an angle displaced relative to the scanning direction as successive build layers are fused. Lack of fusion can be irregular shaped and may contain unfused or partially fused powder.

NOTE 13—Scanning at reduced scan speed leads to porosity formation, while scanning at a high speed can lead to lack of fusion discontinuities.

4.8.2.4 *Cracking and Delamination*—High intensity (focused) beams and the fast cooling rates in PBF processes can lead to large thermal gradient through a part. The residual stresses caused by cooling can cause delamination of a part from the build plate, or cracking in the part, especially in large parts.

4.8.2.5 *Layer*—Volumetric flaws that grow/propagate within a single layer. Examples include stop/start flaws, horizontal LOF, lamellar cracks/delamination, and skipped layers. Since the Z-height of layer flaws is of the order of a single layer (< 100 µm), and their contained volume will thus be small, their detection can be challenging for incremental step inspection methods such as CT.

4.8.2.6 *Cross Layer*—Volumetric flaws that grow/propagate along the build axis, extending across multiple layers. An example is vertical LOF.

4.8.2.7 *Trapped Powder*—A flaw type unique to powder bed fusion, where unmelted powder not intended for the part is trapped within part cavities.

4.8.2.8 *Inclusions*—Typically caused by contaminants present in the input material or interaction of the melted or sintered deposit with the contaminants in the build chamber atmosphere or vacuum.

4.8.2.9 *Poor Dimensional Accuracy*—Physical dimensions that do not meet engineering drawing, leading in severe cases to an out-of-tolerance part. This type of flaw is caused by stair stepping, relief of residual stresses and associated warping, rapid contraction during cooling after fusion, or sagging under gravity of unsupported areas with vertical overhang or downward facing surfaces. Larger hatch width, larger powder mesh size or filament diameter, and higher power energy source will reduce the geometrical accuracy of smaller feature sizes. Furthermore, X-Y dimensions will tend to be more accurate than Z-dimensions compared with drawing, regardless of the AM process method used.

4.8.2.10 *Residual Stresses*—Rapid cooling from the melt can place certain regions of a part (surfaces or areas with high thermal gradients) in a state of pre-stress, thus reducing the effective structural load that can be applied on the part, thus causing structural weaknesses in the part in regions that have lower mechanical properties compared with the rest of the part.

NOTE 14—For AM processes, residual stresses result from the complex local heating/cooling and resultant inhomogeneous volumetric changes associated with heat flow within the part—further complicated by the geometry, thermal diffusivity, and intrinsic flaws. Residual stresses may act in a positive manner to enhance the performance of a material/structure (for example, surface compressive stresses that delay fatigue crack initiation or slow propagation) or in a negative way to restrict service life (for example, surface tensile stresses that increase crack initiation). Through variation of fabrication parameters, it may be possible to reduce residual stress, but otherwise the part will need an annealing treatment after fabrication. Residual stresses may be measured using portable X-ray diffraction (near surface), magnetic Barkhausen noise analysis (near surface), eddy current (near surface), and ultrasonic methods (bulk).

4.8.2.11 *Balling*—Caused by high scan speed, insufficient energy input, increased thickness of powder layer or high level of oxygen, causing a lack of wetting between the molten input material and the underlying substrate. Balling effects have been shown to lead to pores or voids in PBF parts.

4.8.3 Additive manufacturing processes typically prohibit volumetric flaws with significant height in the build (Z) direction; however, volumetric flaws do occur, particularly in PBF. An additional concern is for planar flaws, such as aligned or chained porosity, or even laminar cracks that form along the build plane. The implication of this is that planar flaws, which are well suited for growth, can be difficult to detect by NDT.

4.8.4 The root causes (process origins) of common flaws and discontinuities, along with applicable NDT procedures, are summarized in Table 1. Table 2 lists common additive manufacturing flaw subclasses. Table 3 shows whether existing NDT procedures can detect flaws in the main flaw classes listed in Table 2, including some NDT procedures not covered in this guide (Acoustic Emission (AE), Leak Testing (LT), Magnetic Particle Testing (MT), and Visual Testing (VT)).

NOTE 15—There are longstanding NDT standard flaw classes for welds and castings. In general, the defect classes for welded and cast parts differ from the flaw classes for AM parts.

4.9 *Process-Flaw Correlation*—Given the range of materials and processes encountered in metal additive manufacturing, the process origins of flaws are still being characterized. However, examples exist. For example, when the energy input is insufficient, successive scan tracks do not properly fuse together and flaws appear along the scan line. In L-PBF parts, incomplete wetting and balling effects associated with insufficient energy input have been shown to lead to pores or voids. In addition, EB-PBF parts can show large voids or cavities extending across several layers when the process parameters

TABLE 1 Nondestructive Test Detection of Typical Additive Manufacturing Flaws[A,B]

Flaw/Artifact[C]	Observed in PBF or DED?	Why?	Post-Process Detection	Comment
Porosity	both	Poor selection of parameters, moisture or contamination of feed material or process environment, inadequate handling, storage, vaporization of minor alloying constituents depending on material feedstock. Errors in precision of beam delivery.	Depending on sample geometry and size of porosity, may be detected using CT/ET[G] /IRT/PCRT/RT/UT	HIP recoverable (may not be fully recoverable)
Voids	both	Powder run out, changes in the energy density of the impinging beam creating keyhole melting or vaporization conditions that entrap voids or create spatter (spherical molten ejecta) leaving holes, and voids that may be covered by subsequent layers of fused materials. System drift or calibration issues may come into play to create conditions of LOF. Bridging of powder in the hopper/poor flow properties.	Depending on sample geometry and size of voids, may be detected using CT/ET[G] /IRT/PCRT/RT/UT	HIP recoverable depending on size (not fully recoverable regardless)
Layer flaws	Unique to AM[F]	Interruption to powder supply, optics systems errors (laser) or errors in data. Contamination of build environment purity (inert gas interruption) or other process interruption such as changing the filament emitter within an electron beam gun. Powder supply blending or mixing between one batch and another, a new lot of filler wire, etc.	Depending on sample geometry and size of flaw, may be detected using CT/ET[G] /PCRT/RT/UT	HIP recoverable depending on size (not fully recoverable regardless)
Cross-layer flaws	Unique to AM[F]	Poor selection of parameters, contamination or degradation of the processing environment. Discoloration (for example, DED-PA of Ti alloys) as detected visually can indicate a process out of control. Error in the precision of the beam delivery.	Depending on sample geometry and size of flaw, may be detected using CT/ET[G] /PCRT/RT/UT	HIP recoverable depending on size (not fully recoverable regardless)
Under melted material/ unconsolidated powder (LOF)	both	Poor selection of parameters, poorly developed and controlled process or a process out of control creating a poorly resolved flaw state. Errors in the precision of beam delivery.	Most probably CT, and PCRT, detectability depends on sample geometry and size	Only fixable during the process
Cracking[D]	Unique to AM[F]	AM PBF failure to clean one alloy powder completely from the build environment prior to processing another, DED large assemblies extensive solidification stresses present within large buildups, There is a host of metallurgical issues associated with crack susceptibility. Extremely large range of potential thermal and mechanical conditions present, across all AM processes, that may lead to cracking are poorly characterized.	Depending on sample geometry and size of crack, may be detected using CT/IRT/PCRT/ET[G] /RT/UT	...
Reduced mechanical properties	both	New powder out of spec or degraded through reuse, poorly developed/controlled process, interruption of feedstock supply. Residual stresses produced by rapid cooling, in a state of pre-stress, thus reducing the effective structural load that can be applied on the part, or causing structural weaknesses in a part in regions that have lower mechanical properties compared with the rest of the part.	Check powder (X-ray diffraction) at end of process and mechanical properties of finished part, stress related reduced properties can be detected using PCRT	...
Poor dimensional accuracy	both	Scaling/offset factors are effected by part geometry, beam intensity, and the density of the powder bed or build platform shift. SLM –scan head/optics problems. EBM – presence of EMF interference.	Usually easy (visually), as part has step on surface, but localized defects may require laser CMM and internal deviations with CT compared with CAD.	...
Inclusions	both	Debris from AM or post processing equipment.	Depends on the nature of the contamination and complexity of part, some inclusions are detectable using CT/ET[G] /IRT/PCRT/RT/UT	Remove all potential sources of contamination; sieve/ analyze powder before and after.
Residual stress	both	Poor selection of parameters.	Usually easy (visually), as part has step on surface, but localized defects may require laser CMM and internal deviations with CT compared with CAD. CT/ET[G] /PCRT	Poor selection of parameters.
Stop/start flaws[E]	both	Consequence of long builds or interruption of feedstock leading to reduced mechanical properties.	Check mechanical properties of finished part; PCRT individual frequencies may correlate also.	...
Surface flaws	Unique to AM[F]	Includes partially fused powder, linear or planar conditions or irregularities. Similar to spatter, undercut, irregular top bead, ropey bead, and slumping noted for welded parts.	ET/MET/PCRT/PT	...
Trapped powder	Unique to AM[F]	...	Most probably, CT or PCRT detectability depends on sample geometry and part size.	...