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Standard Guide for Additive Manufacturing of Metal — Finished Part Properties — Methods for Relative Density Measurement[1]

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1. Scope

1.1 In this standard, guidelines for measuring post-manufacturing relative density of metallic additive manufactured (AM) parts and density assessment test specimens are given.

1.2 In this guide, standard test methods commonly used to measure part relative density and details any procedural changes or recommendations for use with PBF-LB parts are referenced. Extensibility to other types of metallic AM processes may be considered on a case-by-case basis with user discretion.

1.3 This guide is intended to be applied during the selection process of methods to measure the relative density of AM parts to balance cost, accuracy, complexity, part destruction, and part size concerns.

1.4 Pore size, shape, and distribution and their implications relative to the AM process and material are beyond the scope of this guide; however, each method's ability to obtain these metrics is discussed in the context of the various density measurement methods.

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

1.6 *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.*

1.7 *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]

B311 Test Method for Density of Powder Metallurgy (PM) Materials Containing Less Than Two Percent Porosity

B923 Test Method for Metal Powder Skeletal Density by Helium or Nitrogen Pycnometry

B962 Test Methods for Density of Compacted or Sintered Powder Metallurgy (PM) Products Using Archimedes' Principle

E3 Guide for Preparation of Metallographic Specimens

E494 Practice for Measuring Ultrasonic Velocity in Materials by Comparative Pulse-Echo Method

E1245 Practice for Determining the Inclusion or Second-Phase Constituent Content of Metals by Automatic Image Analysis

E1935 Test Method for Calibrating and Measuring CT Density

E2782 Guide for Measurement Systems Analysis (MSA)

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

2.2 *ISO Standard:*[2]

ISO/ASTM 52900 Additive Manufacturing — General Principles — Fundamentals and Vocabulary

3. Terminology

3.1 *Definitions*—Terminology relating to additive manufacturing in ISO/ASTM 52900 shall apply.

3.2 *Acronyms:*

3.2.1 *2D*—Two-dimensional

3.2.2 *3D*—Three-dimensional

3.2.3 *AM*—Additive manufacturing

3.2.4 *CAD*—Computer-aided design

3.2.5 *HIP*—Hot isostatic pressing

3.2.6 *LOF*—Lack of fusion

3.2.7 *NDT*—Nondestructive testing

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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.

3.2.8 *PBF-LB*—Powder bed fusion-laser beam

3.2.9 *XCT*—X-ray computed tomography

4. Summary of Guide

4.1 The relative density of a PBF-LB part, in the context of this guide, is expressed as a percentage relative to 100 % dense material (for example, 99.5 % density refers to the presence of 0.5 % observed porosity) or relative to a standard theoretical material density value (see 4.2 for further explanation). With respect to AM, relative density can be an indicator of process capability and resultant material quality. Density of a part, expressed as a percentage, is referred to as relative density within this guide.

4.1.1 Density traditionally takes on another meaning, specifically how much material, by mass, is contained within a certain volume. Realize that there are many different material density definitions, all of which are the mass of the material divided by its volume. It is the definition of the volume, and what is included in the volume, which differentiates the different material densities.

4.2 Some relative density measurements in this document rely on comparing the measured material density of the part, with units g/cm^3, to the theoretical material density, the standard measured value used to reference the true material density value. The intrinsic property of material density, with units g/cm^3 will not be used. Instead, material density references the measured material density of the part for the remainder of this document. Special care must be taken when selecting the theoretical material density value used in the calculation of relative density. It is recommended to use a trusted source, such as verified database, where theoretical material density values of sufficient precision can be obtained.

4.3 Different methods can be used to measure the relative density of finished AM parts. Relative density measurements are crucial in evaluating fabrication quality, as low-relative density values are indicative of process-related defects. In this guide, the following relative density measurement methods will be discussed in detail.

4.3.1 The Archimedes method measures material density by comparing the dry mass of a part and the submerged mass of the part. The measured material density is then compared with the theoretical material density to determine relative density.

4.3.2 Gas pycnometry measures the material density by the volume of gas displaced by the solid part and divides the mass of the part, determined with a separate measuring device, by the volume. This measurement is then compared to the theoretical material density to determine relative density.

4.3.3 XCT captures data from X-ray measurements at different angles. These data are reconstructed to determine relative density by identifying the process-induced defects in grayscale images and quantifying them in terms of voxel size.

4.3.4 Ultrasonic testing measures material density based on the velocity of ultrasonic waves passed through a part and reflected to the transmitter. The velocity measurement is used to calculate material density, which is then compared to theoretical material density to determine relative density.

4.3.5 Metallography and serial sectioning are destructive methods that captures 2D images of specimen sections. Relative density is calculated via area fraction of pores.

5. Significance and Use

5.1 *General:*

5.1.1 This guide is intended to support PBF-LB process and parameter development, part acceptance criteria, and process control tests.

5.1.2 *Flaws and Defects*—Fabricating fully dense parts continues to be a challenge in AM as the process intrinsically introduces volumetric flaws into a part reducing the part relative density (that is, increasing porosity or the presence of small voids in a part making it less than fully dense) and mechanical performance.

5.1.2.1 When a flaw reaches a size, shape, location, or criticality that makes it becomes unacceptable for part acceptance, it will be referred to as a defect.

5.1.2.2 Flaw or defect formation is governed by the manufacturing process, build parameters, feedstock, and geometric factors. Therefore, accurate measurement of fabricated part relative density is an important initial step in determining part and process quality.

5.1.2.3 The quantity, size, and shape of the volumetric flaws influences mechanical performance of a part, particularly under cyclic loading. These data could indicate irregularly shaped (for example, LOF pores or microcracking) or spherical porosity (for example, keyhole or entrapped gas porosity) and determine acceptability by assigning criteria. While these metrics can be quantified, in this guide, the general capabilities of each method to capture this data will be highlighted, but detailed recommendations on these data types will not be made and rather the focus will be on relative density measurements.

5.1.3 *Uncertainty and Error*—Users should consider that each measurement technique considered in this guide has differing sensitivities to various sized features. The measurement methods will also have different potential systematic errors or measurement uncertainties due to sampling sizes, detection resolution, effect of surface condition, experimental set-up, or reliance on a theoretical material density. It is important that these effects are taken into consideration as well as the natural statistical variability in the measurements. Multiple measurements of nominally identical test specimens should be made to enable the quantification of statistical uncertainty. Systematic uncertainty contributions will not be reduced by greater numbers of repeated measurements. When measuring specimens with relative densities close to 100 % quantification of systematic uncertainty for the selected measurement technique(s) becomes more critical to separate measurement and systematic variation from variation driven by the AM process. Differing levels of rigor can be applied when determining the role of uncertainty and variation depending on whether the measurement is in support of process development (for example, identifying appropriate fabrication parameters) or part acceptance (for example, part qualification).

5.1.4 *Repeatability and Reproducibility*—As uncertainty and error can be introduced into the measurement process through operator variation. Performing gage repeatability and