INTERNATIONAL

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Standard Guide for Additive Manufacturing of Metals – Powder Bed Fusion – Measurement and Characterization of Surface Texture[1]

This standard is issued under the fixed designation F3624; 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 is designed to introduce the reader to techniques for surface texture measurement and characterization of surfaces made with metal powder bed fusion additive manufacturing processes. It refers the reader to existing standards that may be applicable for the measurement and characterization of surface texture.

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

1.3 *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.*

1.4 *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 *ISO Standards (normative):*[2]

ISO 1302 2002 Geometrical product specifications (GPS). Indication of surface texture in technical product documentation

ISO 4287 2000 Geometrical product specification (GPS)—surface texture: profile method—terms, definitions, and surface texture parameters

ISO 4288 1996 Geometrical product specification (GPS)—surface texture: profile method—rules and procedure for the assessment of surface texture

ISO 21920 part 2 2022 Geometrical product specifications (GPS) — Surface texture: Profile. Part 2: Terms, definitions and surface texture parameters

ISO 21920 part 3 2022 Geometrical product specifications (GPS) — Surface texture: Profile. Part 3: Specification operators

ISO 25178 part 1 2016 Geometrical product specifications (GPS). Surface texture: Areal. Indication of surface texture

ISO 25178 part 2 2012 Geometrical product specifications (GPS). Surface texture. Areal. Terms, definitions, and surface texture parameters

ISO 25178 part 3 2012 Geometrical product specifications (GPS). Surface texture: Areal. Specification operators

ISO 25178 part 600 2019 Geometrical product specifications (GPS). Surface texture: Areal. Metrological characteristics for areal topography measuring methods

ISO 25178 part 601 2010 Geometrical product specifications (GPS) — Surface texture: Areal — Part 601: Nominal characteristics of contact (stylus) instruments

ISO 25178 part 604 2013 Geometrical product specifications (GPS). Surface texture: Areal. Nominal characteristics of non-contact (coherence scanning interferometry) instruments

ISO 25178 part 606 2015 Geometrical product specification (GPS). Surface texture: Areal. Nominal characteristics of non-contact (focus variation) instruments

ISO 25178 part 607 2019 Geometrical product specifications (GPS). Surface texture: Areal. Nominal characteristics of non-contact (confocal microscopy) instruments

ISO/ASTM 52900 2021 Additive manufacturing — General principles — Fundamentals and vocabulary

2.2 *ASME Standards (normative):*[3]

ASME B46.1 2019 Surface Texture (Surface Roughness, Waviness, and Lay)

2.3 *National Physical Laboratory (NPL) Guides:*[4]

NPL GPG 11 2001 Good Practice Guide No. 11: The Beginner's Guide to Uncertainty of Measurement

[1] This guide is under the jurisdiction of ASTM Committee F42 on Additive Manufacturing Technologies and is the direct responsibility of Subcommittee F42.01 on Test Methods.

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

[3] Available from American Society of Mechanical Engineers (ASME), ASME International Headquarters, Two Park Ave., New York, NY 10016-5990, http://www.asme.org.

[4] Available from NPL.

NPL GPG 37 2014 Measurement Good Practice Guide No. 37: The Measurement of Surface Texture using Stylus Instruments

NPL GPG 116 2010 Measurement Good Practice Guide No 116. The Measurement of Rough Surface Topography using Coherence Scanning Interferometry

NPL GPG 129 2013 Measurement Good Practice Guide No. 129: Calibration of the Metrological Characteristics of Areal Contact Stylus Instruments

NPL GPG 127 2013 Measurement Good Practice Guide No. 127: Calibration of the Metrological Characteristics of Coherence Scanning Interferometers (CSI) and Phase Shifting Interferometers (PSI)

NPL GPG 128 2012 Measurement Good Practice Guide No. 128: Calibration of the Metrological Characteristics of Imaging Confocal Microscopes

2.4 *JCGM Documents (normative):*[5]

JCGM 200:2012 International vocabulary of metrology - Basic and general concepts and associated terms (VIM)

JCGM 100:2008 Evaluation of measurement data - Guide to the expression of uncertainty in measurement (GUM)

3. Significance and use

3.1 Determining optimal strategies for the measurement and characterization of surface texture is necessary to increase confidence in the assessment of surfaces and in any further comparisons and correlations sought between manufactured surfaces, manufacturing processes, and desired functionality. Further, measurement and characterization of surface texture have implications in the field of tribology and in the determination and specification of part quality. This guide is designed to provide users of measurement technologies in both industry and academia with good practice for optimizing measurements of surfaces produced by metal powder bed fusion (PBF) manufacturing processes. While the focus of this guide is on surfaces produced by metal PBF, some of the referenced methods may also be appropriate for surfaces produced by other manufacturing processes.

4. General concepts

4.1 *Additive manufacturing:*

4.1.1 Additive manufacturing (AM) is defined in ASTM 52900 as "the process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies". The direct creation of fully metal parts, where the final part is wholly metal as built is currently commercially limited to only a few process categories. While the principles of this guide could be applied to other processes, the guide is focused more specifically on PBF. PBF is divided into two sub-technologies, determined by the mechanism by which energy is applied to the powder bed, particularly: laser-based PBF (PBF-LB) and electron beam-based PBF (PBF-EB).

4.1.2 In the PBF process, the powder and materials, build parameters, support removal, post-processing and surface finishing operations all contribute to the final surface topography. These factors will also influence the surface features that can be observed and measured. As such, some understanding of the relative scales of the features produced will be useful to understand the limitations of various measurement technologies as well as to assist with measurement planning.

4.2 *Metrology:*

4.2.1 According to the JCGM 200:2012 International vocabulary of metrology - Basic and general concepts and associated terms (VIM), metrology is the science of measurement, including all theoretical and practical aspects of measurement, measurement uncertainty and its field of application.

4.2.2 Measurement is the process of obtaining quantity values that can be attributed to a quantity, referred to as a measurand, with an associated measurement uncertainty. Measurement uncertainty is defined as the parameter that characterizes the dispersion of the quantity values of the measurand. National Physical Laboratory (NPL) Good Practice Guide No. 11: The Beginner's Guide to Uncertainty of Measurement is a guide to evaluating measurement uncertainty, and more detailed descriptions can be found in the JCGM 100:2008 Evaluation of measurement data – Guide to the expression of uncertainty in measurement (known as the GUM).

4.3 *Surface texture metrology:*

4.3.1 Surface texture metrology (often referred to as surface metrology) is used to characterize local deviations of a surface from a defined form (typically a perfectly flat plane). Simply put, surface metrology deals with geometrical irregularities present at a surface, but not those that contribute to the form or shape of the surface. The ASME B46.1 Surface Texture (Surface Roughness, Waviness, and Lay) covers much of the content found in the ISO standards. In this guide, we primarily refer to "surface texture" (that is, filtered surface data), over the unfiltered "surface topography" as most characterization pipelines used for AM surface measurement involve some filtration. However, some pipelines, such as those used in multiscale topographic characterization (see 4.7.5), do not necessarily feature filtering and characterize the whole measured topography.

4.3.2 *Measurement technologies*—There are seven technologies capable of measuring surfaces that are currently covered within the ISO 25178-60X series.

4.3.3 Of these, the following are most commonly applied in the measurement of AM surfaces:

4.3.3.1 Contact stylus,

4.3.3.2 Coherence scanning interferometry,

4.3.3.3 Focus variation microscopy, and

4.3.3.4 Confocal microscopy.

4.3.4 In addition to these approaches, X-ray computed tomography and other conventional form measurement technologies have increasingly been used to measure parts to extract surface information (**1**).[6]

4.4 *Surface texture characterization:*

4.4.1 Surface topography refers to the overall surface structure of a part, surface form refers to the underlying shape of

[5] Available from BIPM.

[6] The boldface numbers in parentheses refer to the list of references at the end of this standard.

that part and surface texture refers to features that remain after the form has been removed. The surface texture can either be separated out by filtering the topography into components of waviness and roughness or assessed as a primary profile or primary surface. Waviness refers to the lower spatial frequency components of the surface texture, and roughness to the higher spatial frequency components. These terms are standardized within the context of profile-based surface texture analysis and applied to areal (that is, relating to, or involving an area) surface texture as well. An example visualization of the filtering process is presented in Fig. 1. An example of the filtration process and its effect on an example measured profile is seen in Fig. 2.

4.4.2 For areal surface texture, there is a different naming convention to that for profile analysis, where the surfaces are defined by the filters applied and how they limit the scale on the surface. The equivalent to the roughness profile is the 'S-L' scale-limited surface, whilst the primary and waviness profiles are referred to as 'S-F' and 'L-F' surfaces, respectively (for clarity, it is important to correctly define filter nesting index values). An example visualization of the filtering process is presented in Fig. 3.

4.5 *ISO 21920 profile measurement:*

4.5.1 A surface profile is defined as the profile that results from the intersection of a surface with a specified plane, that is, the plane in which the measurement is taken. When characterizing profiles, the following procedures should be followed, as covered in ISO 4287, now updated into ISO 21290. It should be noted that ISO 4287 and 21920 differ in procedure (particularly with respect to the order of the form removal and λ_s/S-filter operations), with ISO 21920-2 and ISO 21920-3 now following the areal approach found in ISO 25178-2 and ISO 25178-3, respectively. Their inconsistencies are a part of the standards Profile measurements are acquired in a direction perpendicular to the lay of the surface, that is, the direction of the dominant manufacturing process marks. For AM surfaces, this lay may be the weld tracks on the top surfaces or the build layers on side surfaces. For surfaces where the lay is unclear (which can occur on some AM surfaces) profile measurements should be performed in a number of different directions and resultant parameters averaged for the surface. Further information and guidance on profile measurement and characterization can be found in NPL Measurement Good Practice Guide No. 37: The Measurement of Surface Texture using Stylus Instruments.

4.5.2 While the procedures for profile measurement are covered in ISO 4288, now ISO 21920, it should be noted that the filters specified to characterize different surface textures were designed for conventionally machined surfaces, rather than AM surfaces. AM surfaces often have *Ra* values much higher than 6 µm, which, as specified, would require a 40 mm evaluation length (with an λ_c filter cut-off length of 8 mm). However, recent research has been used to show that this relatively large evaluation length is not required to successfully

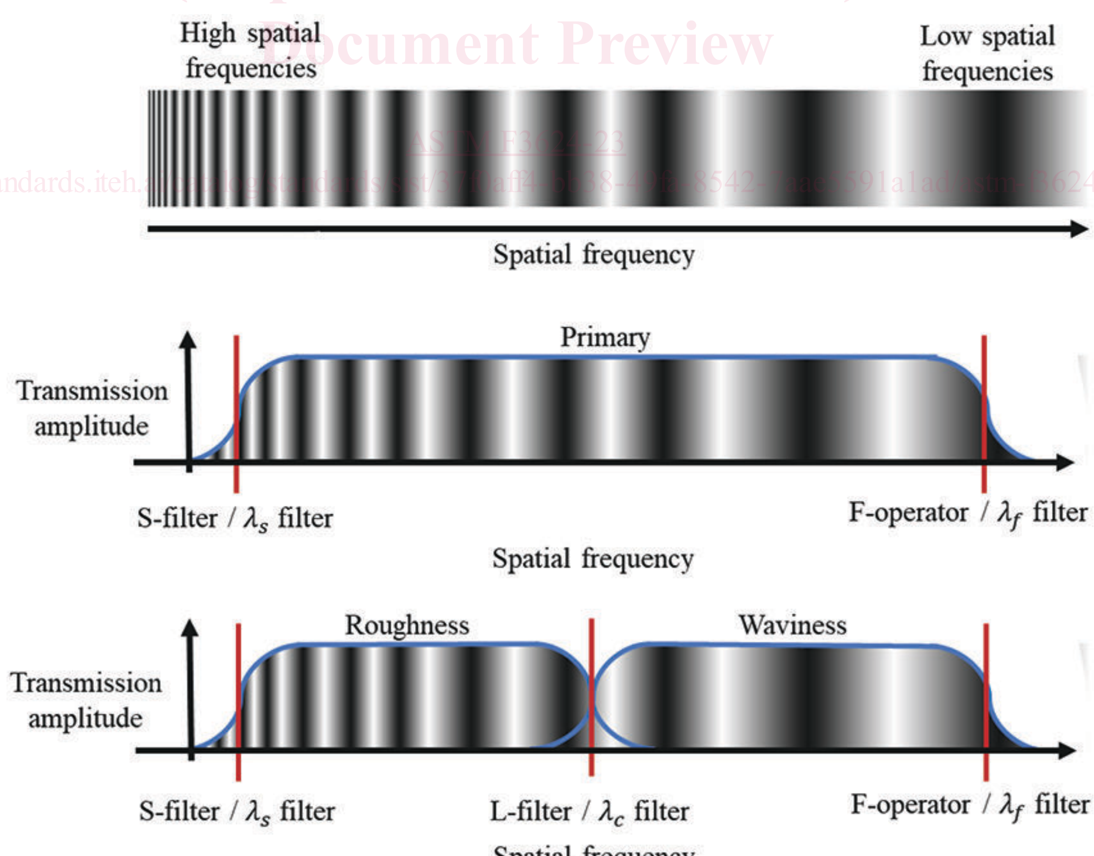

FIG. 1 Effect of filters on the spatial frequencies of a surface texture measurement

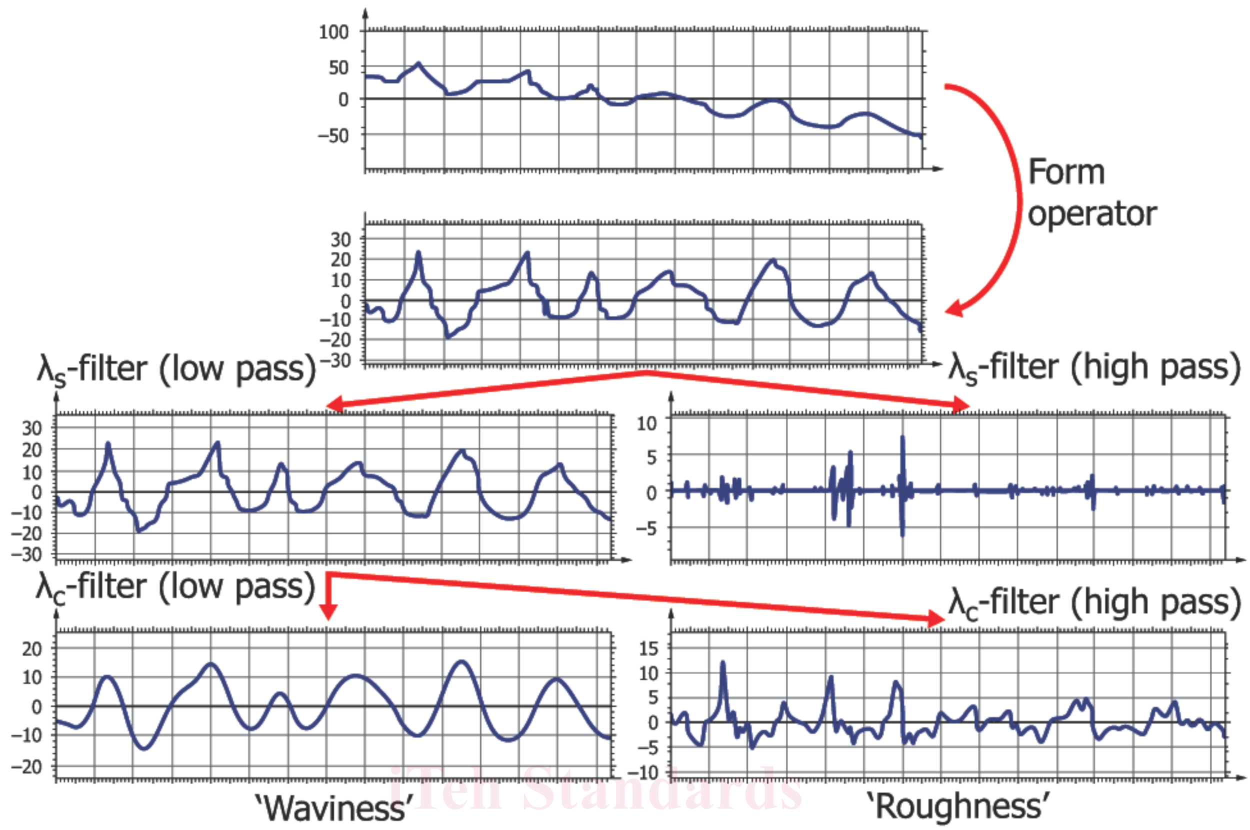

FIG. 2 Example surface topography filtering process (profile); following ISO 4287

characterize AM surfaces, and a smaller 8 mm evaluation length (with a λ_c filter cut-off length of 2.5 mm) is generally sufficient (**2**). Additionally, it is important to note that the choice of filter cut-off length should be based on the features of interest, which can be smaller than 2.5 mm.

4.6 *ISO 21920 profile parameters:*

4.6.1 The roughness parameters, prefixed by an *R*-, refer to those generated only on the roughness surface shown above in Fig. 2. Equivalent parameters, prefixed with *P*- and *W*-, refer to those computed on the primary and waviness profiles, respectively. Most (but not all) *R* parameters are calculated for each sampling length and averaged to calculate a parameter for the evaluated profile.

4.6.2 For profile-based characterization of surface texture, the most commonly employed parameter is *Ra*, which is used to characterize a wide range of engineering surfaces. However, there are many more amplitude, spacing, hybrid and curve-based parameters that can be used to characterize an assessed profile. *Rq* and *Rz* are often used to give a general assessment of roughness and to compare with other conventional surface measurements. Parameters that target the peak features on the profile (*Rpk*, etc.) may be useful for characterizing particle features on the surface. However, profile measurement and parameters are fundamentally limited by an inability to discriminate between some types of features on a surface because they lack areal information. For example, a roughly spherical particle and an elongated weld track may appear similarly in a profile measurement. *Rsk* and *Rku* may provide indications of the presence of peaks or pits, and the relationship between the height distribution and a Gaussian distribution.

4.7 *ISO 25178 areal measurement:*

4.7.1 Areal surface measurement results in a '2.5D' representation of the surface, with height information being a function of the two dimensions of the plane, so that heights are represented as $z(x,y)$, defined within ISO 25178. This data is commonly considered 2.5D as opposed to 3D, because datasets are only capable of handling one *z* value for each value of *x, y* (meaning the data cannot account for the presence of undercuts in the surface). The sampling area refers to the *xy* plane in which a measurement is performed; typically, this is the size of the field of view of an optical measurement system but can also be made of stitched measurement areas or an array of parallel profiles. Unlike in profile characterization, the components of the surface are not defined explicitly as waviness and roughness but are defined by the filtering methods applied to them.

4.7.2 As in the profile measurement case, where the λ_c filter cut-off length of 2.5 mm was sufficient for PBF surfaces, for areal measurement the L-filter nesting index can be set at 2.5 mm, meaning a (2.5 × 2.5) mm areal measurement would be sufficient to capture enough detail to characterize a PBF surface (**2**). A measurement size of (2.5 × 2.5) mm is usually sufficient for most metal AM surfaces, and L-filter nesting indices between 250 µm and 800 µm are commonly employed to extract the weld tracks or smaller features, or both, that exist on the PBF surface for characterization. It is always recommended to set the L-filter nesting index at a value determined

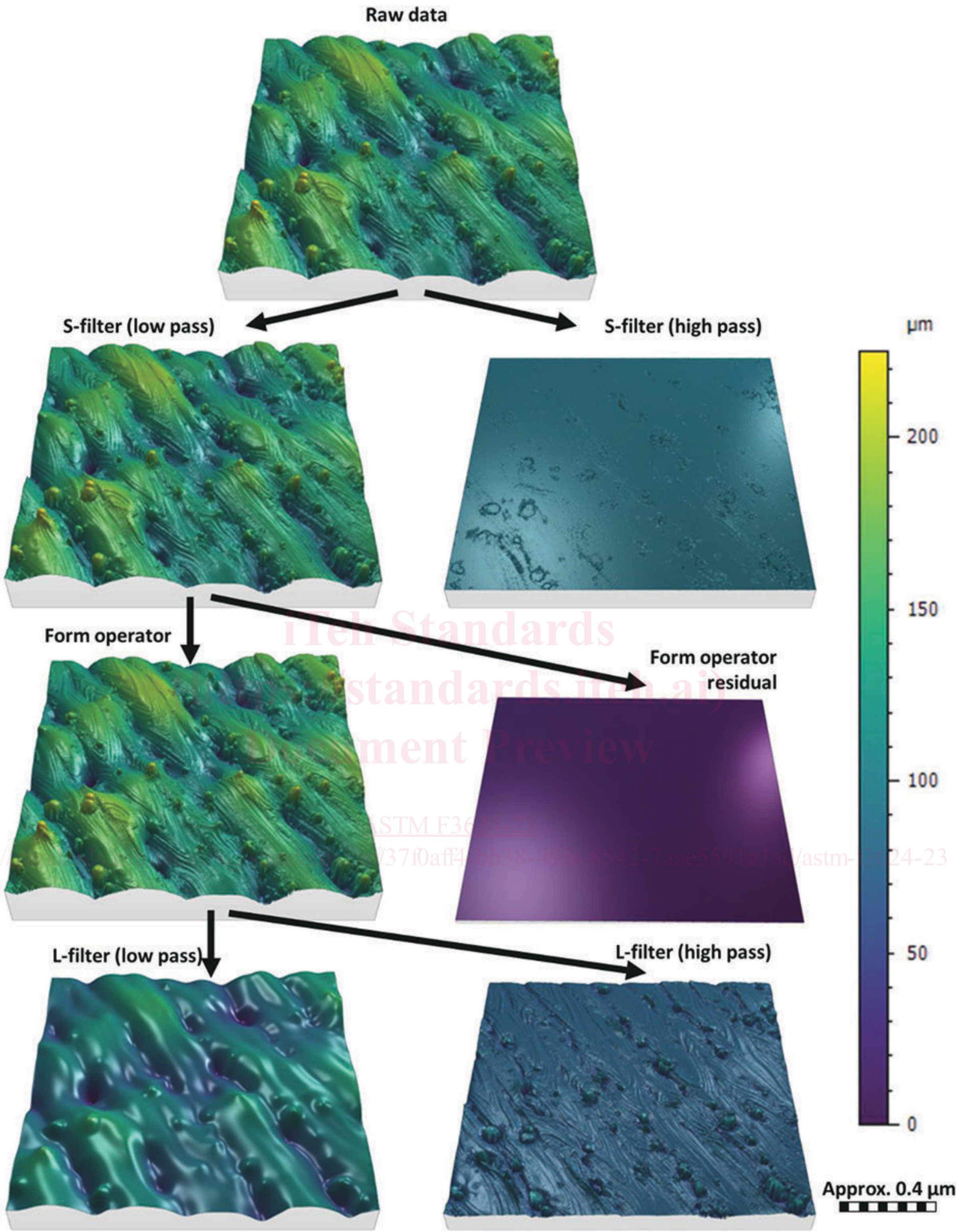

FIG. 3 Example surface topography filtering process (areal)

to ensure a valid separation of the features of interest from the underlying larger-scale surface components.

4.7.3 Areal parameters for arithmetic mean height *Sa*, root mean square height *Sq*, and maximum height *Sz*, are commonly used to characterize surface texture for general assessment and comparison. However, these parameters often only quantify a statistical average or the presence of large height ranges and are limited in assessing the shape of the height distribution. The skewness parameter *Ssk* has been applied alongside *Sq* or *Sa* to differentiate upwards facing surfaces from downwards facing surfaces by the nature of the distribution of heights. Functional parameters are applied to assist with the visualization of the height range of the surface to identify peak regions on PBF surfaces, which are related to the presence of particles on upwards facing surfaces.

4.7.4 Feature-based characterisation refers to the methods that characterize the dimensional and geometric properties of individual surface features. These features are any region of the surface whose topography is of interest, with common examples for PBF ranging down from large particles/spatter to individual weld tracks to the weld ripples upon them. Algorithmic segmentation is used on the heights of the surface texture to isolate these topographic structures individually, where dimensional characterisation can be performed. Dimensional assessment includes step-height assessments in terms of vertical height (for example, the height of a specific particle, or depth of a pit), to contour analysis over the lateral measurement (for example, the width of a weld track, or the eccentricity of spatter) and can be either considered individually, or as part of a wider statistic (for example, mean, median).

4.7.4.1 These methods can be found in ISO 25178-2 and represent additional means of characterizing the PBF surface. Feature-based characterization methods are generally applied when a more specific characterization task is to be performed; while texture parameter-based characterization methods provide a holistic statistical summary of a surface, feature-based methods provide specific information about the surface. However, a detailed description of such methods lies beyond the scope of this guide.

4.7.5 Multiscale geometric characterization can be used to characterize the fractal complexity for both profile and areal surface topography, and for establishing scales that are pertinent to providing value in surface metrology. It is known that geometric properties, such as surface lengths, surface areas and surface slopes, change with respect to the scale of calculation of this fractal complexity. By finding the appropriate aspects of geometry and appropriate scale for PBF surface, some correlations and discriminations have been identified in research. These methods can be found in ISO 25178-2 and ASME B46.1 and have been used as an additional method of characterizing the PBF surface, however this lies beyond the scope of this guide.

4.8 *Surface texture measurement for AM:*

4.8.1 *General Considerations for AM*—When measuring lattice structures and other complex internal geometries, surface texture measurements are commonly limited by either the line-of-sight access requirements of optical systems, or the contact access requirements of contact measurement systems. Another general consideration that should be noted when performing measurements of AM parts is the presence of the staircase effect, which is represented by visibly offset layers of a fixed height that approximate the 3D model data. Because of this effect (shown in Fig. 4), local surface angle and layer thickness are often dominant influencing factors on the surface topography of side surfaces.

4.9 *General considerations for PBF:*

4.9.1 There are various manufacturing process conditions that are specific to the PBF process, most notably the interaction between the energy source and the powder feedstock. Some of the more common challenges presented by PBF surfaces (shown in Fig. 5) are:

4.9.1.1 Large measurement ranges.

4.9.1.2 Sphere-like protrusions.

4.9.1.3 Surface pores (also sub-surface).

4.9.1.4 Changing reflectivity.

4.9.1.5 Large scales of interest.

4.9.1.6 Re-entrant features.

4.9.2 Powder adhered to side surfaces and spatter particles that land on the upper facing surfaces both contribute to the creation of large protrusions on the surface. The surface height range is further increased by the presence of any surface pores or valley regions present. Together, these protrusions and depressions create issues for some measurement techniques that are limited by their vertical scanning range. Using a larger measurement range often means that vertical surface topography repeatability errors are greater than those present when measuring comparably flatter test surfaces.

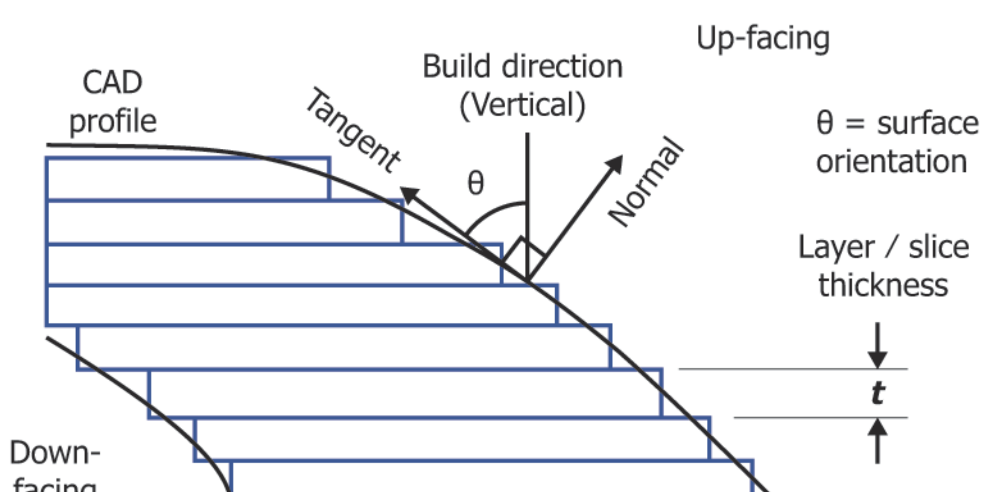

FIG. 4 Graphical representation of the stair-case effect

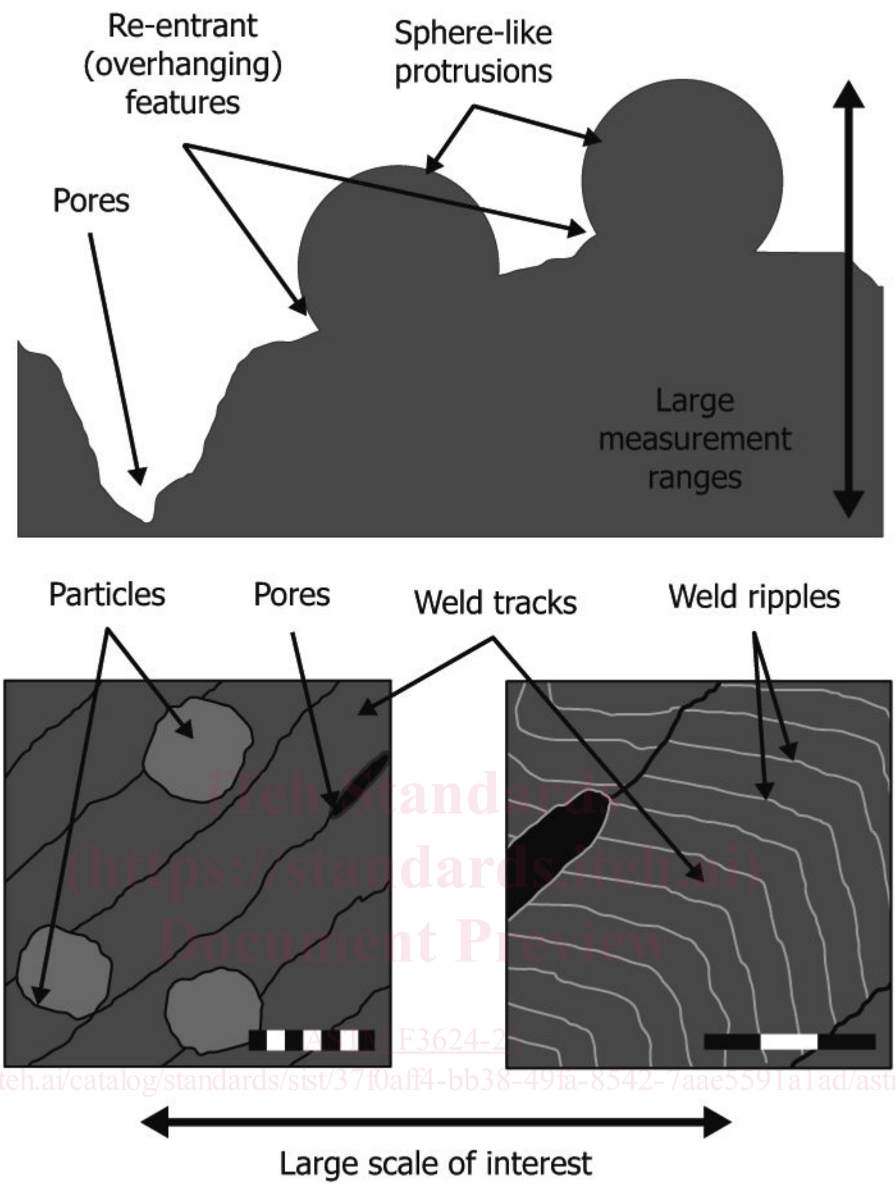

FIG. 5 Example features and challenges of PBF surfaces

4.9.3 Optical properties, such as reflectance, vary significantly across the materials used in PBF, as well as across single PBF surfaces. Such variations can cause issues for optical measurement techniques. Because of the presence of pores and deep valleys, there is often a need to use high intensity light settings to capture light reflected from within these regions. Simultaneously, metal PBF surfaces have smooth regions that result from the melting and solidification process, which have a high reflectance and can easily produce over-saturated images in the optical instrument when high intensity illumination is employed. Together, these factors make the determination of suitable optical measurement settings difficult.

4.9.4 The surfaces typically manufactured by metal PBF are very rough, which can be seen through visual inspection as well as measurement. Metal PBF surfaces generally have a wide range of spatial wavelengths. These surfaces often have large scale components hundreds of micrometers in size (such as the weld tracks or layers), as well as spatter, un-melted and semi-sintered powder and other exogenous particles that appear as features tens of micrometers in size. There are often also even higher spatial frequency components (such as weld ripples of few micrometers in size) present on the surface. In the following section, these surface features are examined in more detail, followed by recommendations for appropriate measurement technologies to overcome the associated challenges.

5. Test surface and test surface preparation

5.1 *Manufacture of metal parts with PBF:*

5.1.1 *As-built Surfaces*—The as-built condition refers to the state of the part made by a process before any post processing is applied, except for the removal of the part from the build platform, supports or the surrounding powder. The as-built surfaces of PBF parts can be understood in terms of the topographical structure and can generally be split between ‘top’, ‘side’, and ‘bottom’ surfaces with side surfaces also