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Surface texture metrology for metal additive manufacturing: a review

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ABSTRACT

A comprehensive analysis of literature pertaining to surface texture metrology for metal additive manufacturing has been performed. This review paper structures the results of this analysis into sections that address specific areas of interest: industrial domain; additive manufacturing processes and materials; types of surface investigated; surface measurement technology and surface texture characterisation. Each section reports on how frequently specific techniques, processes or materials have been utilised and discusses how and why they are employed. Based on these results, possible optimisation of methods and reporting is suggested and the areas that may have significant potential for future research are highlighted.

Contents

1. Introduction

Additive manufacturing (AM) techniques compliment current conventional, subtractive methods by providing additional options to industry: another tool in the manufacturing toolbox. One clear advantage of AM is that it allows the creation of complex geometries and internal features that cannot be produced using subtractive methods. This advantage is primarily due to the tooling path restrictions inherent in conventional manufacturing [1]. By contrast, a current limitation of AM is the degraded dimensional control and surface integrity of specific surfaces. Hence there is often a requirement for complex support structures to be included in the build.

Another significant advantage to AM is the potential for appreciable reduction in time-to-market, gained through factors such as reduced machine set-up and tooling, potential part count reduction and associated assembly time reduction. AM is now being used to make production parts in high-value applications where complex-

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ity and customisation are key advantages, such as hearing aid shells [1]. The 2013 UK Foresight Report [2] highlighted the role of AM in the mass personalisation of low-cost products as a likely fundamental change in manufacturing in the near future. It is perhaps too early to state whether AM is a *third industrial revolution* [3] but AM certainly has significant industry-specific advantages in relation to conventional manufacturing processes.

Part of the reason for adoption by the aerospace and medical industries since 2011 is that standard high-performance engineering materials currently used in these industries, such as titanium 6Al4V, 17-4 PH stainless steel, cobalt chrome and Inconel 625, are all suitable materials for AM production. Of possible metal AM build processes, powder bed fusion (PBF) has been the process with the greatest economic impact [4]. Consequently there has been more research in to PBF than other metal AM processes, such as layer object manufacture, material extrusion, material jetting and directed energy deposition (DED).

1.1. Surface texture metrology for additive manufacturing of metal parts

This review paper focuses on reporting current research on the use of surface texture metrology solutions for metal AM technologies. Surface metrology is defined as the measurement and characterisation of surface topography [5]. Topography is the term typically used to describe the entire geometric information associated with a surface shape and its features, where shape is typically referred to as form [5]. This review focuses on texture and not form (see Ref. [6] for a review of form metrology for AM).

Per ISO 25178-2 [7], surface texture is the scale-limited surface remaining after a series of operations applied to the primary extracted surface. The F-operation removes form (if required) from the primary surface. This is followed by application of an S-filter to remove small scale lateral components and L-filter to remove large scale lateral components.

Further definitions of surface texture have been proposed, for example by Leach [8]:

Surface texture is the geometrical irregularities present at a surface. Surface texture does not include those geometrical irregularities contributing to the form or shape of the surface.

Surface texture metrology can play an enabling role in AM-related manufacture and research, beyond its use as a tool for verifying compliance to specific surface texture requirements. Surface texture metrology can be used as a means of gaining insight into the physical phenomena taking place during the AM manufacturing process, through examination of the surface features generated by the process and walking backwards through the complex and intertwined network of cause-effect relationships between the involved physical phenomena (for example, conduction heat transfer, balling effects (spheroidisation of the melt pool)) [9,10], hydrodynamics and Marangoni circulation (mass transfer due to the surface tension gradient on the melt surface) [11] and process control variables (for example, powder configuration, laser or e-beam spot size, power level and scan speed) [4]. Surface texture metrology becomes a powerful exploration tool, increasing knowledge of the process and ultimately allowing the creation of improved AM processes capable of producing specification-compliant parts.

1.2. Contents of the review

Whilst this review focuses on the broad topic of surface texture metrology as applied to AM research, it is important to clearly state the boundaries of which specific subjects are covered and which are not:

- As stated in Section 1.1, surface texture metrology involves the measurement and characterisation of surface texture; therefore, this paper does not deal with the subject of form/shape inspection and verification, which is typically covered by form metrology [6].
- Given their recently acquired industrial importance, this work focuses on AM technologies for metals. Many of the reported findings and conclusions may also be applicable to other materials (such as polymers and some types of composites), but metals and metal-related issues are the primary area of investigation. Additional references discussing surface metrology issues for non-metal AM processes will be discussed when they have relevance to metal parts.
- Surface texture metrology deals with both measurement (i.e. the process of acquiring topography data from a surface) and characterisation (i.e. the process of extracting useful quantitative information from topography data). Both aspects are covered by the review.

This review deals with inspection, not monitoring. In other words, it reports the current literature on the challenges of how to measure a surface and extract useful information in a one-off, self-contained scenario, generally performed on the completed component after removal from the build chamber. In-situ process monitoring is beyond the scope of this review. Refer to Ref. [12] for an overview of the current literature on monitoring and real-time control for AM processes.

1.3. Reviewing method

To prepare this review, relevant references were retrieved from the main scientific online databases, with publication dates ranging from 1997 [13] to the date of submission of this manuscript. To reorganise the contents retrieved from the literature into a manageable taxonomy, a series of relevant themes was prepared, and initially posed in the form of questions (see Table 1).

In the remainder of this review, each section is dedicated to answering one or multiple questions from the list in Table 1. A general justification/explanation of each subject is reported first, followed by an analysis of the literature contents for the specific subject, and finally, a brief summary of the main findings for the section. Achievements and open issues are discussed, and future opportunities and challenges are reported in the conclusions.

2. Industrial domains, AM processes and materials

Understanding which industrial domains are addressed most often in the literature on surface texture metrology for AM may give an indication as to where industrial and academic research is currently heading, and research results may indicate the key challenges to be faced. Typically, along with the industrial application comes the need for using specific materials. Being able to use an AM technology with a material defined by design specifications is one of the major challenges for the emerging AM technologies, since many technologies have been conceived and developed around very specific materials. Application, material and AM technology often form a strong bond, which must also be considered in AM surface texture measurement planning, execution, data analysis and data processing.

An investigation of the current literature on surface texture metrology for AM indicates that research is still at an early stage and currently lacks strong connections to real applications or application requirements. Most research is still at the stage where surface texture metrology is used to understand manufacturing process capability in a general sense, and application-specific requirements have not yet been introduced in a systematic way. Many references

Table 1
Questions outlining the main themes covered by the review.

Review section	Question and examples
Section 2: Industrial domains, AM processes and materials	What is the industrial domain or application covered, if any? Which AM processes have been researched? For example a specific product or a generic industrial domain, such as aerospace. What are the metrological requirements and challenges specific to that domain (if any)?
Section 3: Types of surfaces investigated	What types of surfaces are investigated? For example, horizontal, tilted or vertical plane, freeform, external, internal, complex 3D (such as trabecular structures), random and structured. Are the surfaces from actual products or artefacts specifically designed for surface investigation? What are the metrological challenges specific to each geometric configuration? Does the surface configuration help verify process capability and provide insight into the manufacturing process?
Section 4: Surface measurement technologies and strategies	What measurement technology is used? What strategy has been used to retrieve reliable data? For example, contact stylus, confocal, focus-variation, interferometric. Areal or profile? What are the challenges and capabilities of each in relation to the specific application scenario and AM process-material combination? What are the metrological challenges connected to the specific process and material (for example, high-roughness, undercuts, reflectivity, potential damage from contact probes)?
Section 5: Surface texture characterisation	How is the measurement data processed and analysed? For example, computation of texture parameters, and the application of filtering techniques. What are the specific considerations and challenges for surface metrology? Which surface texture parameters are most sensitive to surface changes during post-processing operations?

discuss the importance of AM processes in specific industrial contexts, but few actually translate this into context-specific research. We note here a few exceptions. There has been examination of bio-compatible materials and their suitability for manufacturing medical and dental parts (including surface texture discussions) [14,15]. The fatigue performance for as-built, machined and polished samples [16] has been investigated, as has the effect of surface roughness on the efficiency of electromagnetic horn antennae [17].

Materials and processes in AM have typically evolved in combination. Specifically concerning metals, the types of AM processes that have been studied in the literature on surface texture metrology for AM is reported as follows:

Powder bed fusion (PBF): [10,14–16,18–56].

Directed energy deposition (DED): [57–63].

It can be seen that the majority of metal-based AM processes investigated are PBF systems. Figs. 1 and 2 show typical as-built surfaces of metal parts generated by the two most common PBF processes: selective laser melting (SLM, see Fig. 1) and electron beam melting (EBM, see Fig. 2). It is evident that a high degree of irregularity is present at different scales of observation. Powder particle sizes and geometries influence the texture of the fabricated layers and partially melted particles can be clearly seen in the scanning electron microscope (SEM) micrographs. Many instruments can be configured to measure surfaces at a wide range of scales-of-interest, for example a focus variation instrument may have selectable objective lenses with magnifications ranging from ×2.5 to ×100. These SEM micrographs illustrate the challenges of selecting the appropriate scale-of-interest, measurement instrument and configuration (see Section 4) together with appropriate surface texture parameters and filtering (see Section 5).

The role of specific materials in terms of the challenges they generate for surface texture metrology has been little investigated in the literature. Most considerations on measurement challenges are not specifically related to material properties, but to the topographies of the generated surfaces. Although generally not as rough as other AM processes such as DED and fused deposition modelling (FDM), PBF processes tend to generate rougher surfaces than turned or ground surfaces. PBF surfaces present significant measurement challenges due to the frequent discontinuities, vertical walls and re-entrant features. The nature of such topographies is equally challenging for contact and non-contact measurement methods. Styli may jam against the steep sides of surface asperities causing jump/slip temporary loss of contact and even tip damage; optical measurement may be affected by high slope angles, multiple or diffuse reflections and high image contrast. Softer materials pose the additional challenge of being at risk of damage under the stylus passage, which in turn leads to the need for carefully selecting stylus tip radii and contact forces [64]. It is also known that surface properties may change significantly as a result of post-processing, for example a PBF surface/material combination, which may be dull with little specular reflection presenting minimal challenges for some optical instruments, may become highly specularly reflective after post-processing by grinding or machining, or may change colour and require a more challenging optical measurement setup. Each reference reviewed generally discusses research focussed on a single material type as processing conditions and parameter settings are highly material dependent.

The following is an analysis of metal types used in the references:

In the analysed pool of approximately 60 references where material type and AM build process are specified, nickel alloys cover 5%, Inconel 625 being the subject in 75% of this research. Inconel 625 is a high-strength corrosion-resistant nickel chromium super-alloy with a useable temperature range from cryogenic to 982 °C, making it a good choice for liquid-fuelled rocket engines, gas turbine engines and cryogenic tanks [65].

Aluminium alloys, such as AlSi10Mg, cover 5% of the examined literature on surface texture metrology for AM [28]. Calignano et al. [45] investigated the influence of process parameters scan speed, laser power and hatching distance (the perpendicular distance between successive laser scan lines) on the surface finish of direct metal laser sintered (DMLS) AlSi10Mg surfaces, see Fig. 3. AlSi10Mg has good strength, corrosion resistance, low density and high thermal conductivity compared with other alloys and is often found in aerospace and automotive interior AM components, and in functional prototypes [66,67]. In addition to the aforementioned

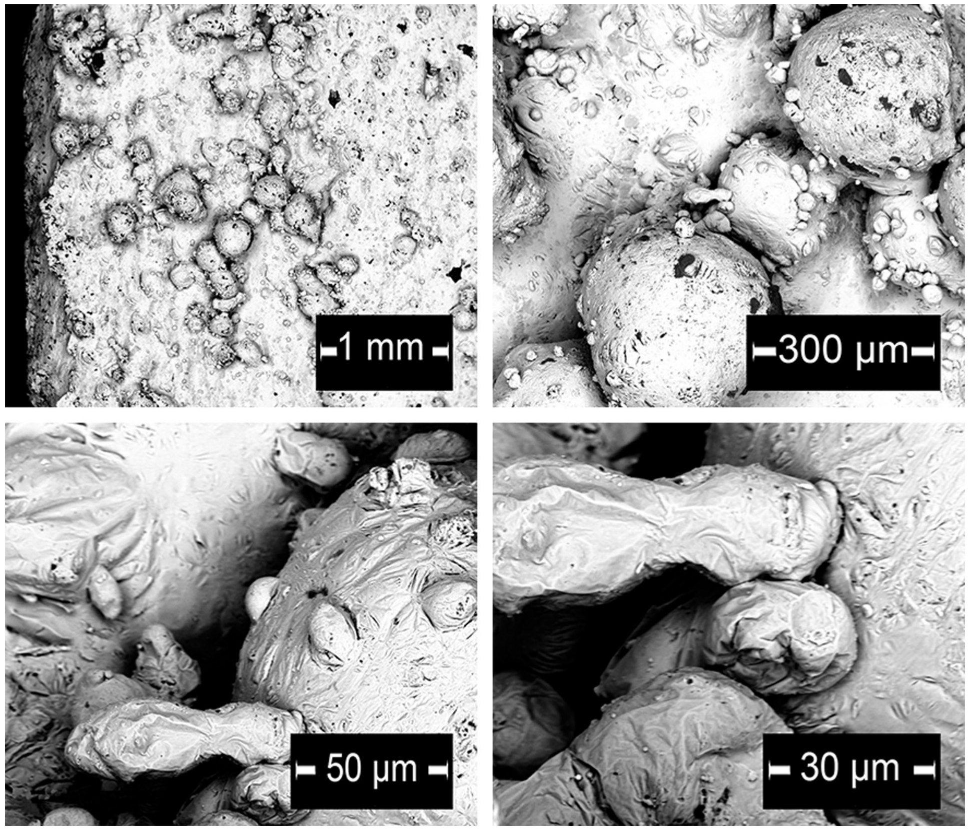

Fig. 1. Multi-scale SEM micrograph of SLM A1Si10Mg part (as built).

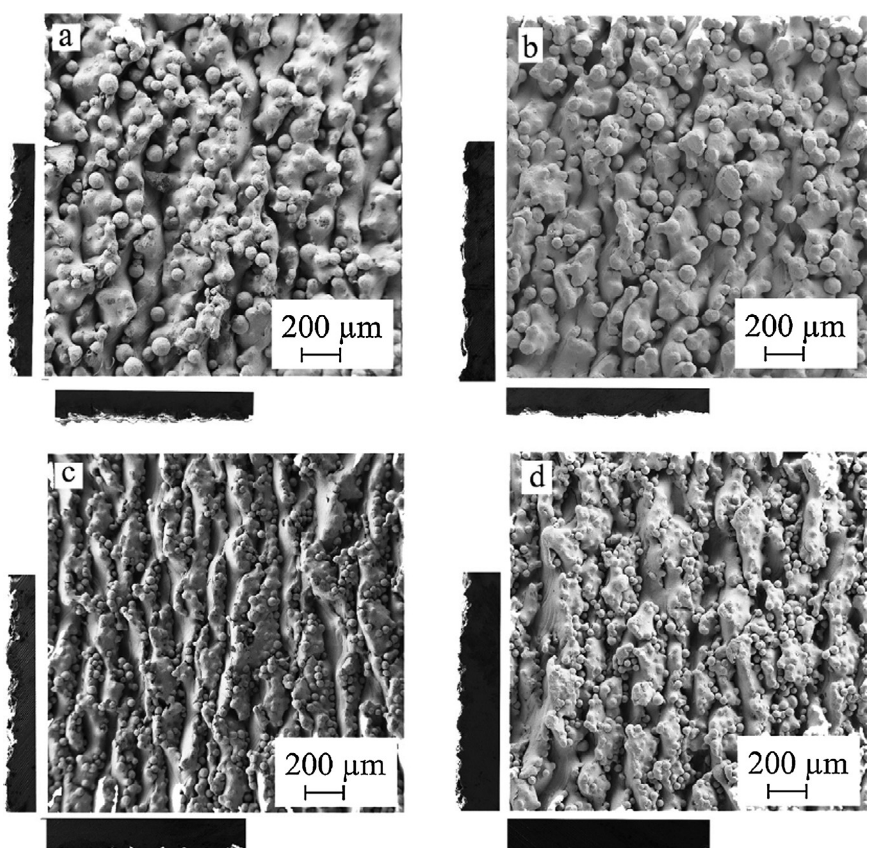

Fig. 2. SEM micrographs of EBM Ti6AL4V part (as built). (a) Built with 45–100 μm powder and 70 μm layer thickness, (b) Built with 45–100 μm powder and 50 μm layer thickness, (c) Built with 25–45 μm powder and 70 μm layer thickness, (d) Built with 25–45 μm powder and 50 μm layer thickness. From Ref. [22].

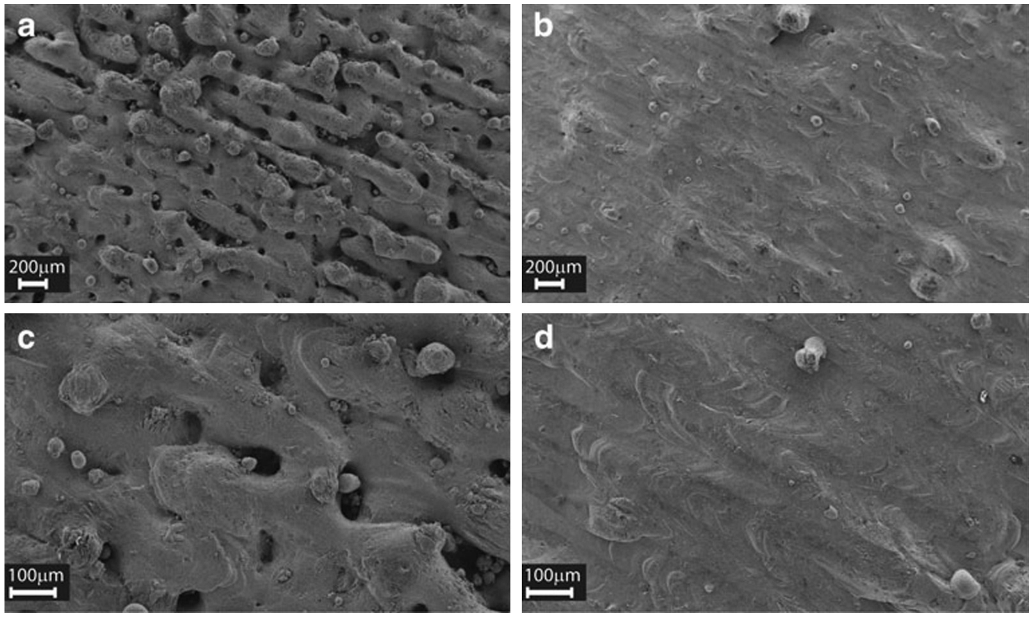

Fig. 3. Field emission SEM images of A1Si10Mg DMLS surfaces. (a and c) Scan speed 1000 mm/s, laser power 190 W, hatching distance 0.2 mm, Ra 24 μm, (b and d) Scan speed 800 mm/s, laser power 190 W, hatching distance 0.1 mm, *Ra* 14 μm [45].

challenges of measuring very irregular surfaces fabricated via PBF processes, aluminium alloy AM surfaces typically raise additional concerns when measured with contact techniques, due to low hardness, possibly resulting in damage from the stylus. Again, consideration should be given to appropriate selection of stylus radii and contact forces [64].

Stainless steel alloys comprise 39% of the examined literature on surface texture metrology for AM. 316L has been used in 70% of this research. 316L is an austenitic chromium-nickel stainless steel with high strength, high corrosion resistance and is particularly resistant to common acids, such as sulphuric, hydrochloric and acetic. Typical applications include exhaust manifolds, heat exchangers, storage tanks, jet engine parts and many parts for marine applications [68]. Other classes of steel, such as alloy and maraging steel, are used in a combined 10% of the total research pool. PBF steel surfaces typically raise the same concerns as nickel and aluminium alloys. Hardness-related concerns about possible damage from stylus instruments are less relevant for steels than for aluminium parts [64].

Titanium alloys comprise 34% of the analysed references. Ti6Al4V is the alloy used in 95% of these references and is the most studied AM metal. Alloys such as Ti6Al4V exhibit good strength-to-weight ratios, high fatigue and corrosion resistance and high temperature performance, leading to many aerospace applications, such as airframe structural components, aircraft skin, rocket, missile and spacecraft parts [69]. Ti6Al4V is also biocompatible, making it an ideal candidate for biomedical applications [14]. Note that concerns about toxicity of vanadium are motivating development of alloys with different elements, such as substituting niobium for vanadium [70].

Refractory materials, such as cobalt chrome and alumina, have been studied along with tool steels and copper alloys [71,72]. There has been limited research published using AM components manufactured from these materials, amounting to a total of 7% of the pool of analysed references. Table 2 shows the types of AM processes used for each material group.

Table 2
AM processes used for each material group.

Material	EBM	Laser	DED
Nickel alloys	0	100%	0
Aluminium alloys	0	100%	0
Stainless steels	0	87%	13%
Other steels	0	83%	17%
Titanium alloys	35%	50%	15%
Others	0	100%	0

3. Types of surfaces investigated

Investigating the surfaces of industry-specific parts initially appears to have the advantage that there is a high probability that the research will address the real conditions and challenges expected in production. However, AM fabrication of metal parts is still in its infancy, thus little research literature has been dedicated to the characterisation of surface texture on actual manufactured products [17]. The use of test artefacts does allow for easier generation and inspection of a wider array of surface types and orientations and is, therefore perhaps, the preferred choice during manufacturing process development, where the main goal is to understand the manufacturing process and its capabilities, so that the process can be improved and ultimately optimised for the target applications.

Many artefacts have been developed for evaluation of surface texture as generated by different AM processes: within the pool of analysed references for this review, 90% were dedicated to the characterisation of artefacts.

Many artefacts have been developed to study the relationships between surface texture and orientation with respect to the build direction. Horizontal, vertical and tilted planes are generally selected for this purpose. Tilted surfaces in particular are useful to highlight the ‘staircase effect’, where the edges of individual layers may be observed [73].

A typical artefact configuration is the truncheon [28,49,74–76] (see Fig. 4). The truncheon has a series of progressively rotated square or rectangular sections. A common configuration includes sections rotated in 5° increments from 0° and 90° [49].

Another artefact designed with planar surfaces at different orientations with respect to the build direction is the angled plate [26,29,77]. This consists of a series of individual plates built at a range of angles to the plane of the build plate. The faceted sphere is designed to include a number of measurement surfaces approx-

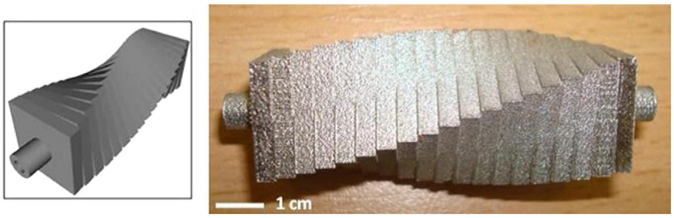

Fig. 4. A typical truncheon artefact [49].

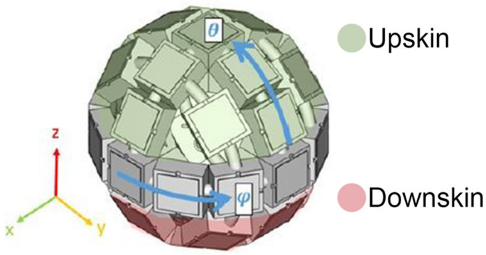

Fig. 5. Faceted sphere artefact. From Ref. [78].

imating a spherical shape [78] and includes a uniform selection of build angles within the build chamber (see Fig. 5).

Plate artefacts with varying spacing between faces have been used to investigate the influence of heat accumulation on surface roughness [19,79]. Some artefacts play a double role, being designed for testing surface texture but also dimensional and geometric accuracy/precision. For example, the National Institute of Standards and Technology (NIST) has included surface roughness measurement areas in their proposed (2012) test artefact [80] (see Fig. 6).

The ASTM F42/ISO TC 261 joint group for Standard Test Artifacts (STAR) is developing a standard for AM test artefacts. One STAR proposed artefact includes seven different artefacts, each designed to check specific AM parameters [81]. One of the seven proposed artefacts is designed for the measurement of surface texture (see Fig. 7).

The surface texture specific STAR artefact is a series of seven platens built at different angles: 0–90° to the horizontal plane, with 15° intervals. The artefact allows for the removal of each platen for easy measurement on optical or stylus instruments. The artefact model would be editable to allow only the construction of those sections required for analysis (perhaps at angles related to the component build angles). Fig. 8 shows the side and top surfaces of an AlSi10Mg SLM component. The layering is not visually apparent in the side surface (a). The hatching lines can clearly be seen on the top surface (b).

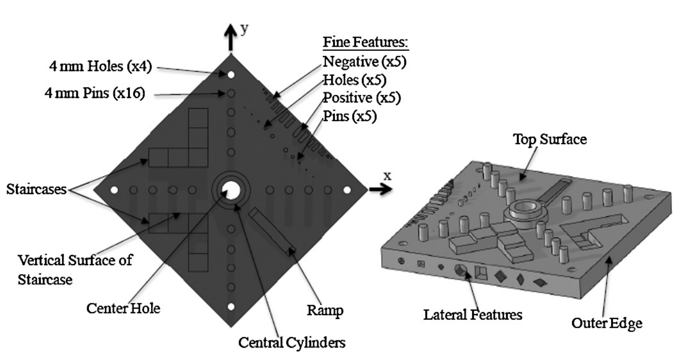

Fig. 6. NIST proposed AM inspection artefact (2012) [80].

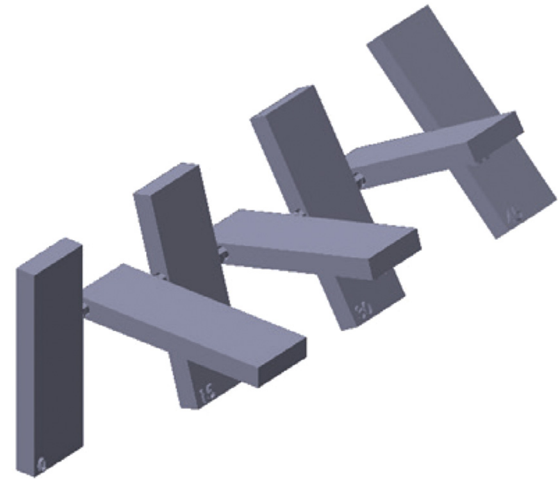

Fig. 7. ASTM F42/ISO TC 261 joint group for standard test artifacts (STAR) proposed surface inspection artefact (2015) [81].

4. Surface measurement technologies and strategies

The spatial frequencies (scales) of interest of the surface to be measured will influence the choice of measurement technology and, in general, technology will govern the metrological quality of the measurement results (for example measurement accuracy and precision).

Both the nature of the material and the structure of the topography influence the choice of measurement technology: contact-based probing (primarily stylus-based measurement) needs to take into consideration the nature of the physical interaction of the probe and the surface, for example whether there is risk of damage to the stylus or work piece during the measurement process. Mechanical and surface properties are heavily influenced by topography and even density: high porosity would lower the strength of the surface layers. The stylus tip radius and cone angle need to be chosen carefully to provide meaningful surface information, with insignificant mechanical filtering of the surface data, and yet be sized to avoid damage when passing over tall, steep sided features that may apply significant lateral loads [82]. Contact techniques should also take into account the accessibility of the surface.

Non-contact techniques, such as focus variation and confocal microscopy, need to take into account the reflective properties of the material being measured. The reflective properties of the AM part may be considerably different from the optical properties of the same material when presented in a polished, flat surface. Non-contact, non-optical techniques (e.g. scanning electron microscopy) and pseudo-contact techniques (e.g. atomic force microscopy) have an array of similar problems when confronted with any specific AM surface.

As the great majority of AM metallic parts are fabricated via powder-based methods, the typical measurand surface is very irregular, and is characterised by sharp protrusions and recesses at multiple scales, with open pores transitioning into closed pores underneath the surface. Some difficult-to-measure surface features are typical of specific AM processes: for example PBF processes produce specific patterns featuring balling, spatter formation, loose or partially melted particles, which are very difficult to measure. Local surface slopes may exceed the maximum measurable limits for measuring technologies, especially optical techniques. Large topographic differences may be observed when comparing an AM metallic surface as generated and the same surface after cleaning. Even more striking is the difference with the same surface after post-processing (typically shot peening [83], laser polishing [84]

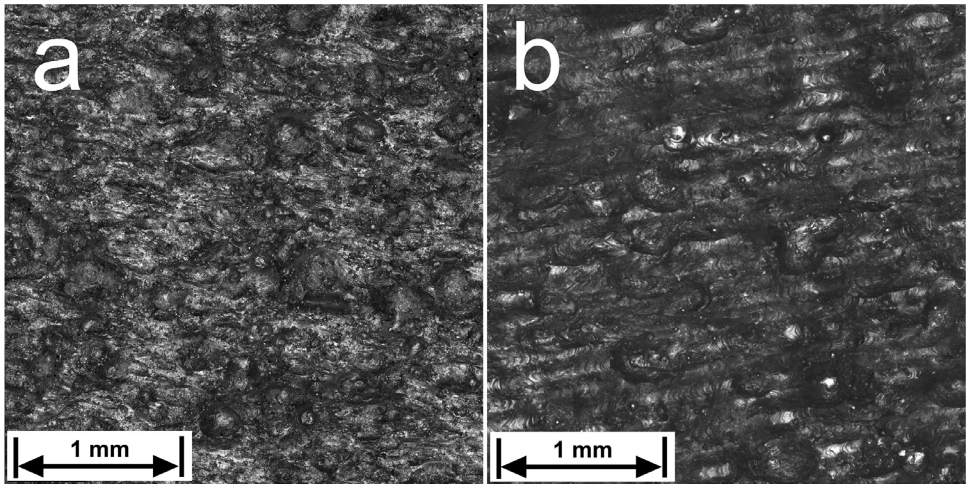

Fig. 8. A1Si10Mg SLM component. (a) Side surface, (b) Top surface.

and/or machining) which essentially produces a new surface. The top surface of a part produced by any layer-based manufacturing process will be influenced by properties, including surface texture, of the previous build layers, contributing to the creation of surface features at multiple spatial wavelengths (scales). Given all the above, the measurement technology should be selected on the basis of the following considerations:

- What are the scales of the features to be characterised?
- What are the sizes and shape properties of the surface features that are more relevant from the standpoint of the function the part?
- What are the sizes and shape of the surface features that, when analysed, lead to a greater understanding of the manufacturing process?

The above questions are linked by the concept of objective-driven measurement: i.e. faced with such a complex geometry, the goals of measurement should be understood first, in order to decide what the priorities should be in capturing information, which in turn should drive the selection of measurement technology together with appropriate measurement settings. Implicit in the above, the most typical objectives are either to analyse how a part conveys function through its surfaces, or to analyse the manufacturing process through the investigation of the surfaces it generates.

In the following, a list of measurement technologies is reported, together with the references that have adopted them for metallic AM surface measurement. The technologies have been divided into sections based on the type of information they can extract from the measured surface.

Profile topography measurement

- Contact stylus [26,27,29,32,45,49,75,76,85–87].

Areal topography measurement

- Confocal microscopy [18,78].
- Focus variation microscopy [26,88].
- Coherence scanning interferometry [89].
- Chromatic confocal microscopy [19].
- Conoscopic holography [86].
- Atomic force microscopy (AFM) [87].
- Elastomeric sensor [90–92].

2D imaging

- Optical microscopy [27,87].
- SEM [18,29,45].

Volumetric

- X-ray computed tomography [25,93].

Other

- Raman spectrometry [85].

It can be seen that the most frequent choice of measurement technology is profile measurement via a stylus-based contact instrument (40% of the examined literature). Profile texture measurement and parameters (see Section 5) are the most ubiquitous industrial surface texture measurement systems. They are generally low cost with a lower (perceived) requirement for operator training and a high comfort level for machinists and inspectors. Historically profile methods have been used for certifying component surface texture complies with drawing and specification requirements and is supported by well-established standards including both ISO and ASME (ISO 3274 [94], ISO 4287 [95], ISO 4288 [96] and ASME B46.1 [97]). Profile techniques are based on scanning and characterising individual profiles traced on the surface. Unless the topography is simple, and characterised by a dominant lay, profile-based measurement is intrinsically limited in its power for capturing topography information, thus making texture parameters limited in terms of the information they can provide relating to part functionality and detailed process feedback [98,99].

The recent shift towards areal topography characterisation is driving the adoption of optical measurement devices based on a range of technologies. The most utilised optical technologies for AM surfaces of metal parts are focus variation microscopy (11% of the examined literature), see Fig. 9, and confocal microscopy (11%). Both technologies can be challenged by the highly irregular nature of the typical topographies being measured, but the acquisition time (at least over a single field of view) is significantly less than raster-scanned techniques. Coherence scanning interferometry, often referred to as vertical scanning interferometry or white light interferometry, is less used (7% of the examined literature) as the highly irregular AM surfaces can present measurement difficulties in terms of local slope and vertical scale of roughness. Similarly, given the highly irregular nature of most AM

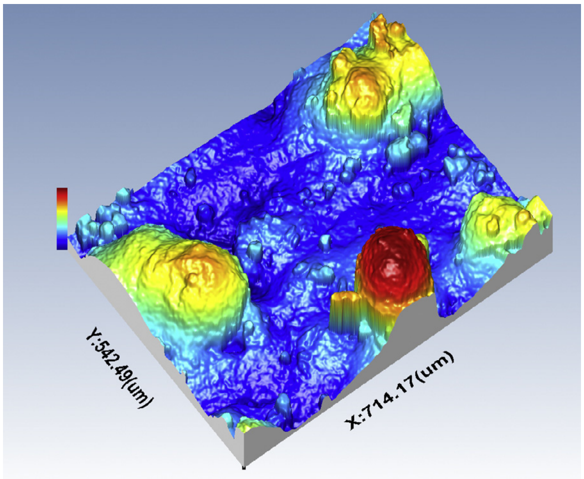

Fig. 9. Focus variation false colour heights map of the top surface of an SLM A1Si10Mg part showing features at various sizes.

metallic surfaces, AFM has been seldom used, both for measurement (vertical) range limitations, and because of the risk of stylus damage. Most researchers involved with the characterisation of AM surfaces will have used some type of conventional 2D imaging, primarily SEM (generally secondary-electron mode) (11%) and optical microscopy (7%). Not being able to provide quantitative information in the vertical (height) direction, 2D imaging techniques have limited use for quantitative surface texture measurement. Thus, 2D imaging is typically reserved for qualitative surface investigation, although in some cases, once calibrated, these instruments have been used for quantitative measurement in the image plane [58]. Despite having been rarely used in the examined literature and initially based on extraction of profile parameter data [25,31,93], X-ray computed tomography (XCT) has potential [100], since, with appropriate data processing methods, surface information can be extracted from volumetric data with no limitations due to vertical walls and undercuts. The most significant advantage of XCT over line-of-sight or contact measurement systems is that surface data can be extracted from the internal surfaces of AM components. Areal surface parameters (per ISO 25178-2) have now been extracted from the XCT volume data of AM components [101]. The main hurdles to widespread adoption of XCT as a means of measuring surfaces of AM parts reside in currently poor spatial resolutions of the measurement, and lack of complete understanding of metrological performance and error sources, necessary for a proper calibration of the surface extraction algorithms (mainly based on thresholding/edge detection) [102].

5. Surface texture characterisation

5.1. Texture parameters

Surface texture characterisation concerns the extraction of texture-related information from the complex topography information obtained through measurement (see Section 4) and producing useful numbers, i.e. quantities that capture salient traits/relevant aspects of the texture such as heights, spacing and distribution of textural features. The ISO specification standards ISO 4287 [95] and ISO 25178-2 [7] define the most frequently adopted parameters in industry and academia: ISO 4287 provides terms, definitions and parameters for profile measurements, while ISO 25178-2 defines areal parameters. ASME B46.1-2009 [97] and JIS B 0601:2013 [103] define analogous sets of texture parameters. However, the ISO standards were exclusively referenced in the reviewed literature.

Areal texture parameters (adopted in 20% of the cases in the analysed literature) require datasets that describe texture in a three-dimensional Cartesian space. These are generally generated using areal topography measuring instruments (which was the case with all the analysed literature). Areal datasets may be created using a profile lateral scanning system which includes an *x*-axis drive, a *y*-axis drive and a *z*-measurement probe [104]. Datasets may also be generated from volumetric measurements, such as from XCT iso-surfaces [101], or derived from the combination of multiple 2D photographs into 3D data (for example photogrammetry from SEM images, shape from shading), not observed in the analysed references. Profile texture parameters (adopted by 80% of the analysed literature) can be computed from datasets obtained by stylus-based instruments, or extracted from areal topography data, or extracted from XCT analysis, a technique that has been employed to provide profile texture information of AM lattice structures [31,93].

By far, the most frequently adopted texture parameter in the literature is the ISO 4287 profile parameter Ra, the arithmetic mean deviation of the assessed profile [18,27,29,45,49,74,76]. Ra is the arithmetic mean of the absolute ordinate values within a sampling length.

The second-most used texture parameter, again a profile parameter from ISO 4287 is Rq, the root mean square deviation of the assessed profile [25,31,105]. Rq is the root mean square of the ordinate values within a sampling length, thus Rq is the sample standard deviation. Other ISO 4287 profile parameters that have been used to characterise the texture of AM surfaces are Rz (maximum height of the profile) [25,31] and Rt (total height of the profile) [57]. The material ratio curve, which represents the material ratio of the profile as a function of level (also known as the Abbott–Firestone curve), has been used for texture analysis [19].

The predominant use of profile texture parameters (in particular Ra) in the characterisation of AM surfaces is consistent with non-AM surface metrology, where areal texture parameters are still gaining acceptance. While ISO 25178-2 contains a comprehensive selection of areal field, feature, spatial, hybrid and functional parameters, with few exceptions, the height parameters have been chosen in the references. As would be expected, the most widely used areal texture parameter in the analysed literature has been Sa, the arithmetical mean height of the scale limited surface. Sa is the arithmetic mean of the absolute of the ordinate values within a definition area. Sa was used in 90% of the references using areal parameters. The areal Sa parameter corresponds to the profile Ra and thus it has proven easier for users to adopt in those environments where Ra was already utilised.

Areal parameters in general have distinct advantages over profile parameters for surface characterisation: surface topography is three dimensional in nature so any analysis of two-dimensional profiles will give an ambiguous or incomplete description of the real surface; for example, a profile measurement taken perpendicularly to the direction of a scratch may produce the same trace as a profile measurement taken of a single pit, see Fig. 10.

Moylan has recommended the combined use of average roughness (Ra or Sa) mean roughness depth (Rz or Sz), skewness (Rsk or Ssk) and kurtosis (Rku or Sku) for the characterisation of AM surfaces [81]. Ssk and Sku are the areal counterpart of Rsk and Rku, respectively the third and fourth-order moments of the probability distribution of heights. In specific configurations, Sku and Ssk may provide indications of relative predominance of peaks or pits, and the relationship between the height distribution and a Gaussian distribution. Likewise, Sz is the counterpart to Rz, the maximum height of the scale-limited surface (refer to ISO 4287 [95], ISO 25178-2 [7] and [107] for further details). Fig. 11 shows examples

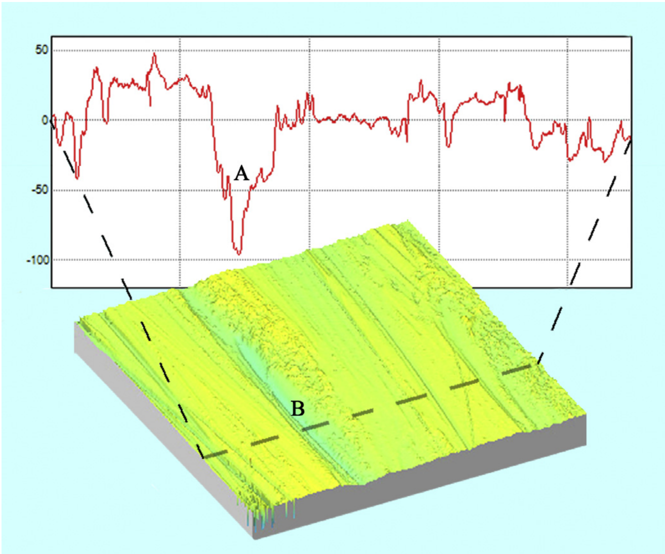

Fig. 10. Profile measurement extracted form an areal measurement, after Ref. [106]. From the profile trace "A" could be a pit or a scratch. From the areal measurement, the same location "B" clearly indicated a scratch.

of SLM Ti6Al4V sample areas before and after vibro-finishing and bead-blasting with Sa values (a–c) together with an SEM image of the post-bead-blasted surface (d) (work performed at The University of Huddersfield).

Results indicated that the following ISO 25178-2 areal parameters were most sensitive to the surface changes during the vibro-finishing process: peak material volume (Vmp), developed interfacial area ratio (Sdr), reduced peak height (Spk) and skewness (Ssk).

Data created using areal surface measurement techniques may be used to characterise specific surface features using a toolbox of pattern recognition systems [7,108–110]. Significant features can be extracted for analysis based on threshold values. The process defined by ISO 25178-2 includes segmentation of the scale-limited surface based on hills (with peaks), dales (with pits), ridgelines, courses and saddle points. Once segmented a change tree based on these segments is developed. The change tree has scaled height distances between the peaks, saddle points and pits. The segmentation process usually results in over-segmentation, so the tree is then "pruned" by combining segments, commencing with the segments with the least height difference between a pit and a saddle point, or peak and saddle point. The process can be visualised by imagining filling all dales with water to an equal depth until the water overflows from the dale with the least height between the pit and the saddle. The process is repeated until a threshold is reached, such as a specified minimum peak to saddle or pit to saddle height value or a specified number of peaks remains.

The segmentation map may then be used as a mask applied to the original data, permitting analysis of the selected features, or similarly features may be extracted and the underlying surface may be analysed. Segmentation and feature analysis have significant application for additive manufacturing. The partially melted powder asperities on the surface of an as-manufactured component (see Fig. 9) may be removed and characterised. Similarly, extracting the asperity data will allow analysis of the underlying surface texture. Without extraction, the asperity data has the potential to overwhelm information from the underlying surface, making analysis difficult. Analysing the underlying surface after asperity extraction has the potential to provide significant informa-

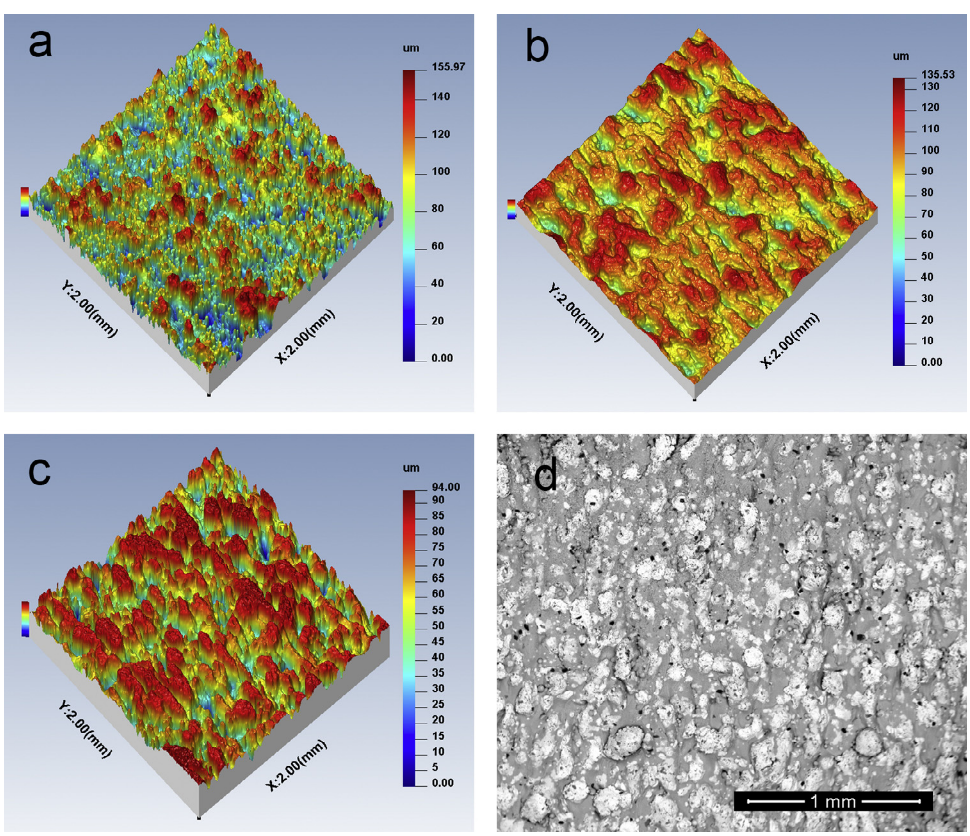

Fig. 11. Ti6A14V SLM part. Focus variation false colour height maps, (a) No processing, Sa 21 μm, (b) post-bead-blasting, Sa 10 μm, (c) post-vibro-finishing, Sa 12 μm. (d) SEM image of post-bead-blasted surface.

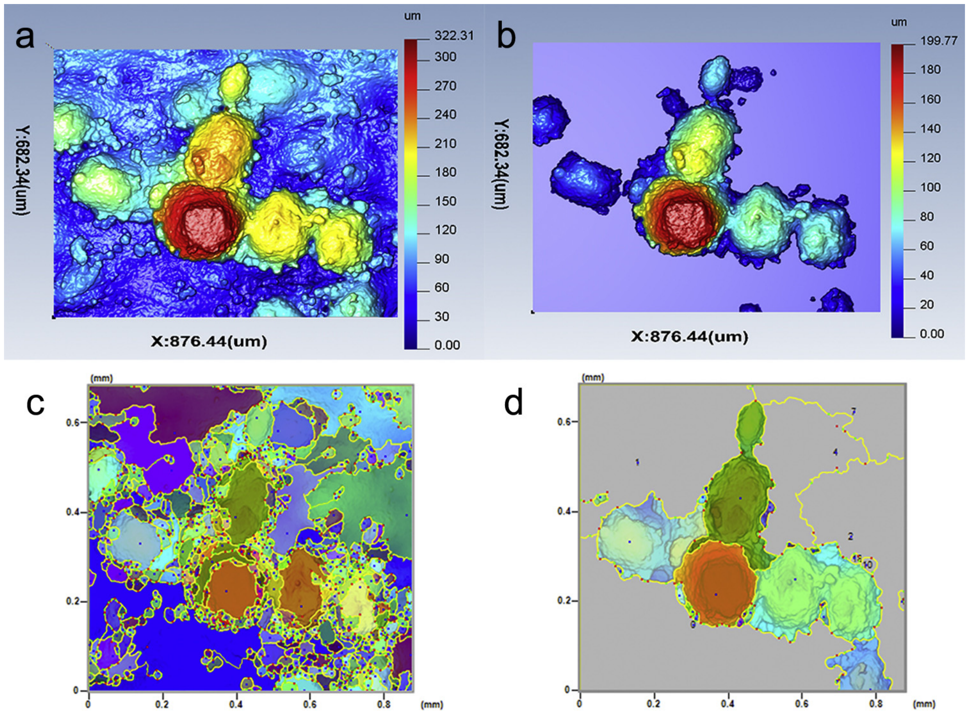

Fig. 12. Feature extraction. (a) False colour height map (original data), (b) After levelling and thresholding, (c) Watershed segmentation followed by 1% Sz Wolf pruning, (d) After 8% Sz Wolf pruning.

tion about the manufacturing process and therefore aid in process improvement and optimisation. Post-processing, such as grit blasting, will remove the asperities but may also destroy information about the surface below. Fig. 12 shows examples for an AlSi10Mg SLM part: focus variation measurement false colour height map (a), a global height thresholding of the levelled surface, showing removed features (b), watershed segmentation followed by Wolf pruning per ISO 25178-2 at 1% Sz threshold (c) and segmentation followed by 8% Sz threshold Wolf pruning showing features that may be extracted for further analysis (work performed at The University of Huddersfield).

5.2. Measurement set-up and processing of acquired data for characterisation

As the values for texture parameters are entirely dependent upon the dataset from which they are computed, attention must be given to the steps that have been taken in order to measure first, and then prepare (process) the topography data for parameter computation. This information is often poorly reported in the literature, making the results typically non-reproducible. Examples of good definition of measurement and analysis include Refs. [27] and [111].

As a general rule of thumb, instruments operating using different principles (contact vs optical) will generate different datasets, even when bandwidth matching has been performed (i.e. the process of making sure the acquired topography datasets cover the same ranges of spatial frequencies) [112]. This is intrinsically related to the measurement technology adopted by each type of instrument and how it interacts with each specific type of surface and material. In most of the analysed references, the type and model of the measurement instrument are appropriately cited. However, only a few references provide all the necessary information needed to replicate the measurement set-up; for example, for optical areal topography instruments, few report the lateral sample spacing or vertical resolution. Once the dataset has been obtained, a series of additional data modification steps can significantly affect the result of texture parameter computation. For example, non-measured points are common in optical measurement; depending on how these are processed (ignored or padded with interpolated values) the texture parameter results vary. Optical measurement techniques produce specific measurement anomalies (for example, a sequence of characteristic spikes known as "batwings" in coherence scanning interferometry, when a step-like feature is generated). The technique adopted for identifying and removing (or attenuating) measurement anomalies should be reported, as it can influence parameter computation. Comparison of the quantity of voids and missing data produced during measurements has been used to select appropriate AM surface measurement equipment, however, no comparison of the effect of padding or interpolating data on the measurement parameters has been reported and research is needed in this area.

After data capture, the form component is removed. When the measurand surface is planar, form is typically removed by simple subtraction of the heights of the least-squares mean plane computed from the dataset. The majority of the research has been performed using custom designed artefacts, manufactured with planar surfaces for ease of measurement (95% of the analysed references). However, curved or otherwise-shaped surfaces typically need a more careful approach, such as removing a profile measurement along the length of a lattice structure [25]. None of the reviewed references included the removal of complex form from a sample. After form removal, filtering of the spatial frequencies is required.

Reporting the spatial frequencies which have been analysed is important as filtered and unfiltered results will vary considerably. The required measurement length or area and appropriate filtering are defined in the standards (ISO 4288 for profile and ISO 25178-3 for areal data sets). Filtering is based on the roughness or scale of the largest significant feature. Many ISO 4287 roughness parameters, such as Ra, Rq, Rsk, Rku are computed on the scale-limited roughness profile, which is obtained by applying the specific series of filtering steps on the raw dataset. The most significant filter operation is the separation of waviness and roughness. This separation is performed by application of a high-pass cut-off filter, λ_c. A low-pass filter, λ_s is applied to limit the high frequency component. A value of Ra provided without indication of (at a minimum) the high-pass filter makes comparison of results difficult. The cut-off filter is reported by 90% of the literature works using roughness parameters.

Areal filtering is performed by the application of low-pass and high-pass filters with stated nesting indexes (equivalent to cut-offs), see ISO 25178-3 [113]. In the literature where areal texture parameters have been used, 70% of the references report values for the nesting indices necessary to reproduce the parameter value. Triantaphyllou et al. [26] investigated the appropriateness of standard cut-off values in AM applications. Ti6Al4V AM components manufactured using SLM and EBM processes had surface Ra values that would require a cut-off (λ_c), of 8 mm per ISO 4288 [96]. The area for optical areal measurements was chosen to be 8 mm × 8 mm, these lengths corresponding to the cut-off wavelength defined for the profile measurement. The areal L-filter nesting index was established using area-scale analysis [114]. The results obtained showed that the L-filter nesting index (and hence, per ISO 25178-3, the lengths of the sides of the measurement area) needed to be no more than 2.5 mm. This would also suggest that a 2.5 mm cut-off for profile measurements (and not the 8 mm based on the surface Ra per ISO 4288) would be sufficient to capture the data required to characterise the sample SLM and EBM test surfaces. This is significant as it reduces the required profile measurement length by a factor of over three and the required areal measurement area by a factor of ten. The result may also permit areal measurements to be acquired without requiring stitched image fields.

If the textural properties vary between regions of the component then consideration should be given to the size of the observational window, number of windows, relative placement, and treatment of the parameters computed within the windows (averaging for example).

In conclusion, the information currently provided in the literature concerning how topography datasets are processed in order to compute texture parameters varies considerably, often making exact duplication of the results difficult. This scenario may improve with time, with increasing awareness of the data processing steps.

5.3. Texture characterisation in relation to part function

While texture parameters, such as Ra and Sa, quantify the mean deviation of the assessed topography, it has long been recognised that surface texture properties should ideally be related to component function [5]. Characterisation should be preceded by an understanding of which surface features are functionally relevant, and which topographic properties are really responsible for functional performance. Studies have been performed correlating surface texture of AM parts with fatigue resistance [16,71,115]. For example in Ref. [71], Ti6Al4V PBF samples (EBM and SLM) were analysed correlating Ra with fatigue life; it was found that as Ra increases from 3 μm to 1000 μm, fatigue life decreases from 10^5 to 10^4 cycles. In the same work, it was also reported that surface defects had the most significant impact on reducing high cycle fatigue life.

More commonly in the reviewed literature surface texture is analysed to increase understanding of the physics underlying the AM process and the effects of individual process parameters on the AM component. A few examples are reported in the following:

- Grimm et al. [78] found a correlation between the surface orientation of SLM parts and Sdr (developed interfacial area ratio).
- Safder et al. [18] researching Ti6Al4V artefacts noted Ra values increased with increasing beam current and decreased with increase in offset focus and scan speed.
- Strano et al. [49] noted upskin surface roughness was influenced by build orientation and layer thickness and downskin surfaces were additionally influenced by laser power.
- Pyka et al. [25] performing chemical etching and polishing of open porous structures, noted that chemical etching primarily removes attached powder grains and electro-chemical polishing decreases the roughness. Hydrofluoric acid was the most effective etching agent.
- Triantaphyllou et al. [26] found that Sa and Sq were suitable measurement parameters for SLM and EBM Ti6AL4V components and that *Ssk* (skewness) differentiated upskin from downskin surfaces.
- Mumtaz and Hopkinson [27] investigating SLM Inconel 625 parts, found that adjusting parameters to achieve minimum top surface and side surface Ra values concurrently was not possible. Parameters that promote a reduction in top surface Ra: increased overlap, reduced scan speed, tend to increase the balling effect and increase side surface Ra. Increasing peak power (to the point of significant material vaporisation) reduces both top and side Ra.
- Beard et al. [85] found that lower scan speed and higher power tend to improve top surface roughness.

Obtaining optimised values for build parameters can be difficult. For example, there is an energy input “sweet spot” below which there is insufficient melting and above which spatter and vaporisation degrade the surface [27]. It was concluded in Ref. [26] that the direction of measurement with respect to lay has little or no effect on the calculated surface texture of SLM and EBM parts. The ASTM F42/ISO TC 261 Joint Group for Standard Test Artefacts (STAR) had found that the effect of the stair-step nature of the layer-by-layer did not dominate the surface texture measurements of PBF platens built at a variety of inclinations [81]. Taylor [4] found that under certain conditions the primary surface lay was not parallel to the laser scan direction.

Research on specific combinations of AM processes and materials, carried out with the help of surface metrology, has led to the determination of optimal configuration parameters for specific process-material combination. However, so far there is a lack of general conclusions of wider applicability.

The relationship between AM process parameters and surface texture is complex and heavily influenced by a multitude of deeply-intertwined physical phenomena; computer-based simulation and predictive modelling has been recognised as a useful method to help understand the relationships between process parameters, and generated topography features [4,116,48,117]. King et al. [118] have modelled the PBF AM process including all factors except the effect of the gas enveloping the build. Currently, due to the process complexity, simulation of one laser pass along a 1 mm laser scan length may take many days on a multi-processor computer system. Commercial companies, such as 3D SIM are working on process solvers that efficiently analyse critical build data and material characterisation to optimise the AM build parameters and process on a part-by-part basis [119].

6. Conclusions

Additive manufacturing (AM) is becoming a strong partner to conventional manufacturing technologies such as casting, forming and machining, for the manufacture of function-critical metallic parts for industrial sectors such as aerospace, medical and automotive.

This review has covered past and current research work on the measurement and characterisation of surface texture for AM metal parts. Amongst AM processes for metallic parts, powder-bed fusion (PBF) has been the subject of the majority of research. As AM technologies experience the transition from prototyping to fabrication of actual parts, a wide array of significant new challenges must be solved. Produced parts must comply to design specifications and standards which include mechanical/thermal/chemical properties, dimensional and surface requirements. These new challenges require a more profound understanding of the AM technology and process, and will ultimately require the development of AM surface texture good practice guidance, specifications and standards.

As the contents of this review have shown, the measurement and characterisation of surface texture for AM processes is challenging. The surfaces of metal PBF components are typically highly irregular, with steep sided and re-entrant features. Relevant surface features exist at a wide range of scales, and care should be taken in selecting instrumentation and measurement scales.

A summary of AM surface texture measurement and characterisation follows:

- Quantitative measurement of surface texture has been predominantly achieved by stylus-based profile measurements. Consequently, the full three-dimensional nature of the topography is not captured.
- Texture characterisation is mostly based on computing ISO 4287 texture parameters on profiles.
- The ISO 4287 Ra parameter is by far the most widely adopted.
- Areal characterisation is increasingly gaining acceptance as the current best solution for obtaining quantitative information about the three-dimensional topography of a surface.
- Areal measurement instrument manufacturers are aware of, and are addressing, the challenges of AM surface texture measurement.
- The majority of existing reference examples where areal characterisation has been used employ ISO 25178-2 texture parameters which are the direct counterpart of the ISO 4287 profile parameters.
- ISO 25178-2 feature parameters, which could help a great deal at isolating surface areas of interest [120] have not been explored in the literature on surface metrology for AM.
- Measurement and characterisation is often not fully reproducible as key information is not reported (for example, void treatment, reduction of measurement anomalies, levelling, filtering and sample spacing).
- In the analysed literature, texture characterisation is mostly performed to gain a better understanding of the AM technology being studied and of its capabilities. This is typical of early-stage development of manufacturing technologies.
- Custom-designed measurement artefacts have generally been used in the research. Artefacts may be optimised for a particular measurement and characterisation scenario.
- There has been limited research into correlation between component functional performance and surface texture.

Metal additive manufacturing presents complex surface metrology challenges, but the significant potential of the process provides incentive to meet these challenges. With the aid of the surface metrology tool box, processes may be understood, improved and optimised. AM-specific surface metrology is in its infancy but will continue to play a vital role as we head toward AM being added to that list of "conventional" manufacturing processes.

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