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A Novel Method for Benchmarking Surface Quality in Additive Manufacturing

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Abstract

The utilization of additive manufacturing (AM) in series applications demonstrates that it has moved beyond the prototyping stage and has reached a higher level of maturity. This means that the decision to use AM is often based on a cost-oriented decision-making process compared to conventional manufacturing technologies. In addition to cost, quality is also a crucial factor that is closely related to the choice of technology. In order to meet the requirements, detailed information on quality aspects and the methods used to derive them is required. Especially in the field of surface characterization, more advanced measurement devices have found their way into international standards. However, due to the inherent complexity of AM, the currently available approaches are not suitable for an industrial implementation. The paper aims to investigate the state of the art in methods and test specimens for determining the surface quality and roughness of additively manufactured parts and to accompany all steps of the process chain. A new test geometry in combination with a proposed methodology will be presented to enable digital surface roughness measurements on an industrial scale. This approach will be validated in a case study investigating the chemical smoothing process of PBF-LB/P components.

Keywords Additive Manufacturing · Powder Bed Fusion · Post-Processing · Surface Quality · Surface Roughness · Test Artifact · Data Analysis

1. Introduction and motivation

Additive manufacturing (AM) describes a process category in which a layer-by-layer approach is used to build three dimensional objects [1, 2]. In addition to the influence of process parameters and material, the layered structure has a decisive contribution on the surface of AM components. The layered structure in combination with the orientation of the part creates a relationship between the surface morphology and the build angle, described as an auto-isotropic character by Grimm [3]. The specification of AM processes is important at this point, as different characteristics are responsible for the overall quality of the components. This study primarily focuses on powder bed fusion (PBF) processes utilizing a laser beam (LB) in the domain of polymer (PBF-LB/P) and metal (PBF-LB/M) production, owing to their industrial application and scale. [4]. Especially in the field of PBF, the range of applications has expanded from prototyping towards series applications [5]. The consideration of AM as a potential alternative to conventional production technologies is based on multiple reasons such as design freedom, customization, flexible production in combination with tool-less manufacturing, and more. Although these advantages are existing since the technologies were invented, the rise in the number of series applications is based on improvements in materials and machine technologies [4]. The potential benefits of AM are driving research and development efforts to improve its efficiency, quality, and reliability. In contrast to the above-mentioned advantages of additive manufacturing processes, however, the cost and quality factors are ultimately decisive. This is the case if AM's unique selling proposition is not the determining factor in the choice of the manufacturing method. Qualification and certification methods for determining component quality and process robustness are critical to the use of any technology in serial applications. Kawalkar et al. [6] states, that the lack of additive manufacturing standards is a significant factor in limiting the acceptance of AM in all aspects of manufacturing. Santos et al. [7] and Berglund et al. [8] specifically name dimensional and geometric quality analysis as a barrier to the further industrial adoption of AM with difficulties in adapting current measurement systems and techniques.

Standardization of AM is pursued through two major committees, the International Organization for Standardization (ISO), and the American Society for Testing and Materials (ASTM). The research groups ISO/TC 261 and ASTM F42 with subcommittees covering topics such as terminology, materials and processes, test methods, applications, and design. To avoid duplicating efforts, ISO and ASTM signed a cooperative agreement in September 2011 to jointly develop global additive manufacturing standards [9]. An example of the implementation of both organizations is ISO/ASTM 52900 [2] for the standardization of terminology, ISO/ASTM 52902 [10] for standardization of test artefacts, and subsequent documents with consecutive numbers 529xx. A specific overview of standardization efforts and content of addressed ISO/ASTM standards in AM is presented by Moroni et al. [9].

Surface quality is a critical aspect of the overall quality of a manufactured part with a significant impact on its functionality, performance, and design. Achieving the desired surface quality of an additively manufactured component is an essential prerequisite for its successful application and requires detailed information on quality-related aspects and the methods used to derive them. For the determination of quality characteristics, test specimens are usually required, which are used for a capability and limitation assessment or calibration of AM systems [11]. In this case, ISO/ASTM 52902 provides test specimens that are grouped according to the following quality aspects: Accuracy, resolution and surface texture which are measured qualitatively and quantitatively [10]. The measurement of surface texture in form of surface roughness is a method that is well suited for quality determination due to the quantitative determination and degree of utilization in the industry [12]. There is a difference between the well-established 2D tactile and 3D areal measurement (optical), which has significant implications in the choice of measurement methodology for additive manufactured surfaces [13, 14].

This study focuses on the development of a test specimen for the determination of surface roughness of additively manufactured parts using 3D areal measurement methodology. The state of the art and existing standards for test specimens provide the basis in combination with the requirements of AM series-related quality characterization on an industrial level, such as a large-scale manufacturing setting. The proposal of a new geometry follows requirements for a detailed evaluation of the surface roughness depending on the build angle and position within the build volume, as well as the manufacturability, handling, measurability, comparability, and cost. This involves the equal use of the test specimens and measurement methodology for polymer and metal parts. Finally, the proposed methodology is used to characterize the surface roughness of a chemically smoothed PBF-LB/P specimen to investigate the process underlying mechanisms.

2. State of the Art

A variety of test artifacts for the determination of quality characteristics are described in the literature. The focus of this study is the determination of surface texture and roughness and their respective test geometries, which can be related to other quality characteristics depending on the design of the artifacts. The state of the art is introduced by an overview of the development of test artifacts and their quality characteristics.

The first reported test part referred to as the "user part" was designed in 1990 by an SLA (Stereolithography) user group to investigate geometric accuracy in the x-y plane [15, 16]. Kruth et al. [17] proposed a test artifact in 1991 with an inverted U-frame for the comparison of AM processes. Richter and Jacobs [18] were first to define a set of requirements on a benchmark test geometry in 1991, covering the measurability, time-to-build, feature size, and use of material. Ippolito et al. [19] presented a benchmark for the determination of accuracy and surface finish in 1995 and illustrated the need for quality standards. An initial test geometry, specifically designed to assess the influence of build angles and the stair-stepping effect, was introduced by Reeves and Cobb in 1996 [20]. The study names stair-stepping and process related factors responsible for a poor surface finish which is a disadvantage for commercial use. Castillo et al. [21] proposed a test artifact for studying surface quality and manufacturability in combination with different build angles. The study of the initial test geometries for the quality assessments shows a still specific orientation of the test specimen to individual characteristics such as accuracy, geometry, and surface quality. Mahesh [22] proposed a classification in 2004 for test artifacts aimed at assessing quality attributes across three areas. Accuracy and dimensional performance of AM machines, mechanical properties, and process benchmarks to optimize process parameters such as orientation or layer thickness [11]. A preliminary geometric test specimen, serving as an initial example for evaluating process accuracy and stability in accordance with standardization, was previously introduced in 2009 within the VDI 3404 guideline [23]. Moylan et al. [15, 24, 25] proposed a new test geometry in 2012 that serves as an overarching approach for investigating a variety of features build in a single part, published by the Journal of Research of the National Institute of Standards and Technology (NIST). A benchmark of test artifacts and their respective use and measurement methods is provided by Rebaioli et al. [26] and Vorkapic et al. [27]. An approach for the measurement of surface roughness in PBF-LB/M is made by Strano et al. [28] in 2013. The presented geometry named “Truncheon” allows tactile roughness measurements in narrow increments of the build angle. Its shape is characterized by rotated squares around a central axis with incremental steps [29]. Disadvantages are the longitudinal measuring surface, which allows positioning of the measuring section in only one direction, and a high volume of the part. Grimm et al. [13] proposed a spherical test geometry for investigating the surface effects and roughness in AM using 3D areal surface roughness measurements. This study demonstrates the potential of 3D surface parameters compared to the industrial standard of 2D tactile profilometry for AM applications. The configuration of 12 mm × 12 mm square measurement surfaces allows for the assessment of various optically measured surface parameters based on polar and azimuth angles. Additionally, the interference of surface effects with measurement necessitates a significant measurement effort and highlights the importance of considering directionality within AM for quality data determination using conventional methods. Townsend et al. [30] proposed three surface-specific test artifacts for AM use to add this characteristic to the already well covered topics shape and dimension. The test artifacts are designed to provide easy access to optical microscopy measurement techniques for surface-data generation. In contrast to approaches that combine a high number of features into one large specimen, this study provides a rather small geometry that can be built along with the process. Townsend uses the approach by Grimm et al. [13] with a semi-sphere test artifact covering a variety of upskin build-angles between 0° (plane parallel to the build platform) and 90° within the proposed build job. Udroiu et al. [29] presented a methodology for the investigation of surface quality using contact and non-contact surface roughness measurements on a proposed test specimen similar to the study by Strano et al. [28]. Although the approach allows a high level of detail in the measurement between angle and roughness, its size remains a disadvantage despite the comparatively low-volume version of the test specimen. Yap et al. [31] presented three benchmark artifacts to study the influence of process parameters on surface finish, geometrical accuracy and design limitations on features as thin walls for material jetting applications. Pastre et al. [11] showed an overview and the development of a range of AM test artifacts in combination with a design methodology review. A set of recommendations for the design of benchmark artifacts is presented, highlighting characteristics and limitations from manufacturer and metrologist areas. The methodology is demonstrated on a case study on the interaction between the build angle of PBF-LB/M parts on the resulting surface roughness.

The state of the art illustrates the complexity and variety of benchmark components for determining quality characteristics of AM components. ISO/ASTM 52902 was established to provide a comprehensive standard for the application of a benchmark component in conjunction with surface roughness metrology. Beside accuracy and resolution, surface texture is defined as a criterion for the investigation of influencing factors by process parameters, material and AM specific characteristics [10]. Figure 1 shows the test artifact proposed by ISO/ASTM 52902 for investigating surface roughness.

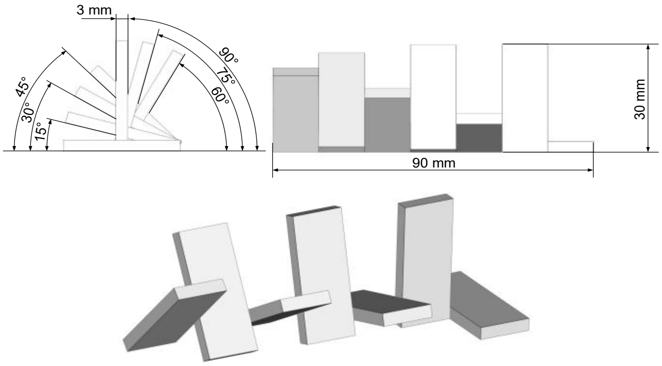

Figure 1: Test artifact with multiple angles for measuring surface roughness by ISO/ASTM 52902.

The test specimen can be used to analyze the angles 0°, 15°, 30°, 45°, 60°, 75° and 90°. 2D line and the 3D areal measurements are proposed for determining the roughness. The specimen is designed in three different dimensions, in which the medium tile has the dimensions 12.0 mm × 30.0 mm × 3.0 mm. To perform the analysis, the tiles must be separated from each other.

In addition to the determination of process related characteristics on the surface texture, the investigation of influencing factors by post-processing methods is equally interesting. This requires repeated measurement between process steps until the finished part. The requirement for a specimen that can be measured in its original shape is therefore a central requirement in the development of the specimen in this study.

The application of the measurement methodology developed in this study is demonstrated through a post-processing technique for chemically smoothing polymer components. The state of the art can be divided into two categories, as described by Tamburrino et al. [32], namely hot vapor smoothing (HVS) and cold vapor smoothing (CVS). HVS involves the use of solvent at room temperature, while CVS operates at higher temperatures using solvent vapor. Baier [33] investigated the influence of different solvents on the surface and material characteristics of parts produced by material extrusion (MEX) in the CVS state. The results showed a strong impact on the surface roughness while also influencing the geometry of the parts. The selection of solvent and the process parameter of immersion time were identified as the most significant influencing factors, which interact in a complex manner with the orientation of the printed parts. Chemical smoothing in the HVS state has gained momentum in industrial applications due to recently published patents [34–36] in combination with available machine technology. The precise control of process temperatures and times enables a significant increase in reproducibility for surface post-processing of polymer components. Current studies highlight the importance of investigating the influences on the mechanical, material, and morphological properties, as well as the functional characteristics, which have a high potential for expanding the application spectrum of AM polymer components [37–40].

3. Measurement Methodology

The development and design of a test specimen follows as set of requirements which range from degrees of freedom in geometry towards the final use within the measurement methodology [7]. The characteristics of the main requirements considered in this paper are summarized below in Table 1 and are explained in more detail in the following.

Table 1: Main requirements for the development of a specimen to evaluate the quality of surface textures using 3D areal roughness measurements.

Measurement methodology	Manufacturability and economic viability	Metrics
• Handling and effort • Process chain accompanying • Possibility of automation • In compliance with test standards	• Support free • Process and material comprehensive • Cost (print time, volume, post-processing)	• Polar angle [Θ] • Azimuth angle [φ] • Position in build volume [x,y,z] • Representative measuring area

➡ Data driven approach using 3D areal roughness measurement techniques.

3.1. Requirements of the Measurement Methodology

The measurement methodology in this study is related to DIN EN ISO 25178 [41] and subsequent documents. The standard describes the 3D areal surface texture parameters and their computation as well as a framework for the measurement of surface texture. This implies a 3D optical approach for the investigation of surface roughness of additively manufactured parts against a conventional 2D tactile approach. This method offers advantages, especially in the field of additive manufacturing, as it enables an independent analysis of surface characteristics to be recorded regardless of directional dependencies. [13]. In accordance with the standard, the measuring range is defined as a user-configurable rectangular area that adheres to filter operations. The determination of the exact measurand depends on the scale of the largest structure on the surface (which is of interest) in addition to filter settings at the lowest level. This procedure is a standard recommendation to be defined in coordination with the measurement methodology for the application. In this study, the objective is to develop a measurement methodology that covers a cross-production process and cross-material approach. As a result, the margin in the choice of measurement operations must be utilized to a certain extend. However, the procedure ensures a consistent measurement for relative comparisons of process characteristics.

A recurring measurement across process steps is a central use case and therefore requirement for the design of the test specimens. This can, for example, be an initial measurement after manufacturing in the as-built condition, with further measurements after blasting and grinding. At the same time, the recurring measurement is supposed to provide a process response to manufacturing parameters. In this context, it must be taken into account that surface effects always result in dependence on the angles of the respective surfaces, i.e. a large number of measurements are required in order to be able to make a general statement. This flexibility of use is also an important requirement for the development of the test specimen. Further requirements are a good handling and a possibility to automate the measurements to a certain degree for a large number of measurements in the industrial context of quality assurance.

3.2. Manufacturability and Economic Viability

The objective of the test specimen is to achieve a tradeoff between a high degree of measurement features (faces) and, at the same time, low production cost and good manufacturability. For a process-qualifying or accompanying use of the specimen, a high number of measurements should be ensured by low manufacturing costs and easy handling. The design and thus the manufacturability of the specimen is adapted to the PBF-LB process for polymer and metal materials, as these are currently widely used for series production. The polymer version of the surface specimen does not need any support structures which makes wall thickness and therefore volume decisive factors. Instead, the metal version requires support structures in certain areas, which depend on the AM system and process parameters. The solution space is constrained to a spherical object with equal dimensions for both metal and polymer materials on the external surface, due to the requirements of the measurement methodology, measurement area, and manufacturability.

3.3. Metrics

The test specimen is supposed to measure the following influencing process variables: polar angle (Θ), azimuth angle (φ), and position (x, y, z) of the part in the build volume. The following angles were selected for the highest possible coverage of the surface, which is still measurable in terms of cost and effort.

- Azimuth angle (φ): 0°, 45°, 90°, 135°, 180°, 225°, 270°, 315°
- Polar angle (Θ): 0°, 10°, 30°, 60°, 90°, 120°, 150°, 170°, 180°

The increments of the azimuth angle cover the main axes x and y of the build chamber as well as the diagonals at 45° to the main axes. The chosen polar angles cover the entire bandwidth from 0° upskin to 180° downskin. The 10° and 170° ranges describe areas with a high degree of the staircase effect. The choice of these two surfaces implies the limitation that the specimen deviates from a sphere. For geometrical reasons, therefore, 10° surfaces are only used in the main axes of the azimuth angle 0°, 90°, 180°, and 270°.

A square with an edge length of 8 mm was chosen for the area to be measured. This allows the recording of small to large scale surface artifacts. To facilitate positioning and to exclude incorrect measurements as far as possible, the total area defined by both angles is chosen to be 12 mm × 12 mm. This ensures 2 mm between the edge of the measuring surface and the reference surface. Along with both angles, the coordinate defines the exact position of the surfaces in combination with the x, y, z position in the build volume. These variables can be used to investigate process characteristics with a high degree of resolution. The user is free to decide whether a level of detail of 100 % is required, or whether the measurement of certain areas is sufficient.

3.4. Design of the Surface Specimen

The described requirements and constraints ultimately determine a geometry for the test specimen. Figure 2 shows the proposed specimen for metal (left) and polymer (right) with a top view equal for both versions (middle).

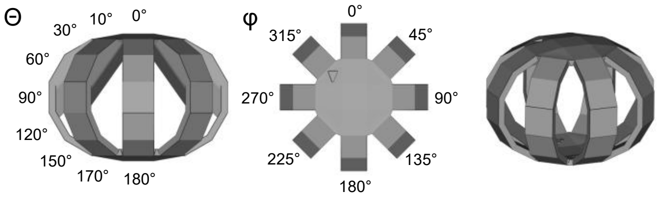

Figure 2: Developed benchmark artifact for surface roughness measurements in metal design front view (left), top view (middle), and isometrical view in polymer design (right).

The figure also demonstrates the incremental steps of the polar- (Θ) and azimuth (φ) angle which results in a total of 50 faces. The inner region of the sample can be used to integrate descriptions of the angles. An arrow on the top sets a reference for the orientation of the specimen. It must always be placed the same way in the build volume as a reference to ensure comparability. A suggestion is to point the arrow in the direction of the machine front. To avoid support inside the metal specimen, wedge-shaped structures are positioned in the downskin area of the top part. Depending on the process parameters and technology, the surfaces must be supported at a polar angle between 150° and 180°.

3.5. Analysis Approach

To obtain accurate measurements, it is necessary to ensure a certain degree of parallelism between the surface being measured and the lens. This angle may vary depending on the manufacturer. For an alignment of the respective surfaces, a fixation can be manufactured with the respective negative. Other solutions for an efficient measurement of many surfaces are a rotation unit, in which the body can be clamped. A robot-guided measurement has been realized by Grimm [3]. Therefore, the measurement methodology always depends on the measuring system.

An advantage of areal surface roughness measurements is a relatively quick generation of data once the surface is scanned. Considering the measurement effort, the specimen in combination with the developed measurement methodology should therefore provide the possibility to generate large data sets. This enables the user to analyze a set of surfaces in respect to the parameter position in the build volume, azimuth- and polar angle from the data. Once the raw data is generated, a large number of parameters can be derived to describe the surface. The parameters can be categorized according to DIN EN ISO 25178 [41] in terms of height, spatial, hybrid, functional, and feature categories. By understanding and analyzing the surface parameters, a statement can be made about the investigated process characteristics. A comparatively high data basis also offers the possibility of making a preselection of parameters based on relative changes in the data, and thus to draw conclusions about technical backgrounds. The two-sided approach (Figure 3) is enabled by a high data basis of optical roughness measurements.

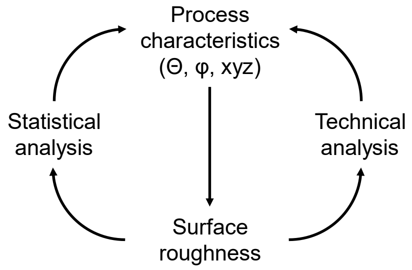

Figure 3: Method for evaluating process characteristics from surface roughness.

The present figure illustrates the methodological framework of analyzing roughness data from a large database (cf. Table 1). The left approach enables a statistical analysis of all data without describing the technical background of process parameters in the first place. This could, for example, be an analysis of all parameter deviations between process steps. Significant advantages arise with larger data sets that include the recording of a large number of surface parameters. On the other hand, the technical analysis of roughness parameters describes an approach that aims to define roughness parameters and thus to analyze specific characterisitcs. A combination of both strategies ensures an economic and fast approach to the investigation of a range of surfaces.

4. Application of the Measurement Methodology within a Case Study

The purpose of this chapter is to present a case study that demonstrates the implementation of the developed measurement methodology in the context of an AM production chain. Chemical smoothing is a well-known method for influencing the surface of PBF-LB/P parts with the advantage of finishing complex designed structures [37, 42]. The process gained interest due to the recent development of industrialized post-processing systems with patents filed between 2011 [36] and 2012 [35]. Although the process holds promise for the use in high-volume component industries, its state-of-the-art evaluation remains limited to this point. The goal is to better understand the mechanism of the smoothing process on the surface and to make a statement about the relative change before and after the treatment. The investigation is based on PBF-LB/P surface specimen manufactured with polyamide 12 (PA2200) material on an EOS P500 machine, equipped with two 70W CO_2 lasers. A total of five specimens are arranged inside the center of the 500 mm × 330 mm × 400 mm build volume. The process parameters are set to the standard EOS print setting, featuring a 120 µm layer height. The system utilizes a standard process parameter set provided by EOS, which was neither visible nor modifiable by the user at the time of the investigation. The powder mixing rate is prescribed by EOS and corresponds to a composition of 50% overflow powder and 50% powder comprising 35% new powder and 65% used powder. After manufacturing, the parts are cleaned from any excess powder through blasting. In the next step, the parts are transferred to a DyeMansion Powerfuse S machine for the chemical smoothing process. The machine is operated using the manufacturer's balanced mode.

The surface roughness analysis is illustrated at a fixed azimuth angle of 0° and polar angles 0°, 10°, 60°, 90°, 120° and 150° in the following. The above-mentioned angles of N = 5 specimens are analyzed before and after chemical smoothing, which results in a total of 60 measurements. The surface roughness is analyzed using a Keyence VR5000 optical profilometer which is based on the structured-light method. The displacement of the projected stripes on the specimen’s surface allows for the retrieval of the height data. The filter operations in this study are set according to DIN EN ISO 52178-3 [41] with an L filter of 2 mm. A plane is used as an F operator to remove any shape deviations of the surface. No s Filter is used in this study since the features of interest are located well above the resolution limit of the measuring system. A first evaluation is performed using the surface parameter S_q which represents the root mean square height and is also known as the standard deviation of the height distribution. Based on the arithmetic mean height S_a, this parameter enables statistically stable results since it is less affected by outliers and measurement noise. Another commonly used parameter is the maximum height S_z. Despite its simple comprehensibility, the parameter is limited in its validity by its sensitivity to outliers. The parameters S_q, S_a, and S_z are defined as shown below.

$$S_q = \sqrt{\frac{1}{A}\iint_A z(x,y)\,dxdy}$$

$$S_a = \frac{1}{A}\iint_A |z(x,y)|\,dxdy$$

$$S_z = |min_A\, z(x,y)| + max_A\, z(x,y)$$

Figure 4 shows the parameter S_q of unsmoothed and smoothed surfaces in relation to the build angle (left) and the corresponding distribution of the data (right) for an initial assessment of the surface.

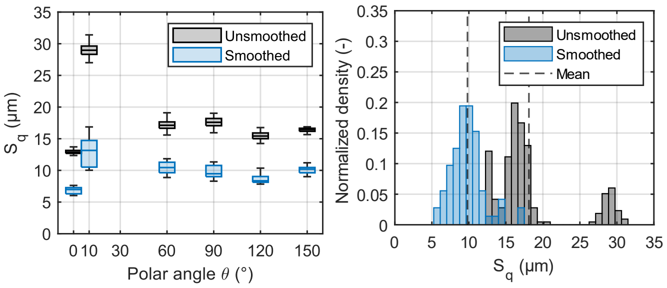

Figure 4: Root mean square height (S_q) of unsmoothed and smoothed surfaces in relation to the build angle (left) with the corresponding data distribution (right).

The unsmoothed specimen shows a mean S_q value of 18 µm with a minimum of 13.5 µm at a polar angle of 0° and a maximum of 29 µm at 10°. An overall decrease can be observed after smoothing of the specimen with the highest change in the 10° surface. The mean S_q value after smoothing is at 10 µm which corresponds to a decrease of about 44 %. The maximum height parameter S_z shows a similar behavior with an overall decrease of 55 % from 230 µm to 103 µm. Both parameters can provide a first idea of the smoothing mechanism but are of limited value without a further investigation.

Further information on the influence of the smoothing process on the surface can be obtained from the distribution of the height values (amplitude density distribution). Based on a normal distribution with the value 0, the parameter S_{sk} describes a right-skewed ($S_{sk} < 0$) or left-skewed ($S_{sk} > 0$) distribution of the height values in z based on the following equation.

$$S_{sk} = \frac{1}{S_q^3}\frac{1}{A}\iint_A |z^3(x,y)|\; dxdy$$

S_{sk} values below 0 refer to a height distribution above the mean plane which corresponds to a plateau character of the surface dominated by valleys. Values above 0 refer to a height distribution below the mean plane and correspond to a surface characterized with peaks. Figure 5 shows the parameter S_{sk} of unsmoothed and smoothed surfaces in relation to the build angle (left) and the corresponding distribution of the data (right).

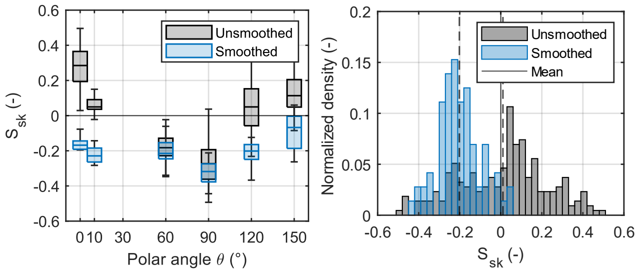

Figure 5: Skewness of the height distribution (S_{sk}) of unsmoothed and smoothed surfaces in relation to the build angle (left) with the corresponding data distribution (right).

Smoothing of the specimen results in a decrease of S_{sk} values of all measured polar angles, except 60° and 90°. Also, the standard deviation of each measured polar angle decreases after smoothing, which results in an overall reduced range of S_{sk} datapoints as seen in the histogram. The negative shift in S_{sk} values below 0 with a mean of -0.2 indicates a surface characterized by valleys rather than peaks.

Figure 6 shows a schematic illustration of a surface characterized by S_{sk} values above and below 0 which corresponds to the unsmoothed and smoothed surfaces.

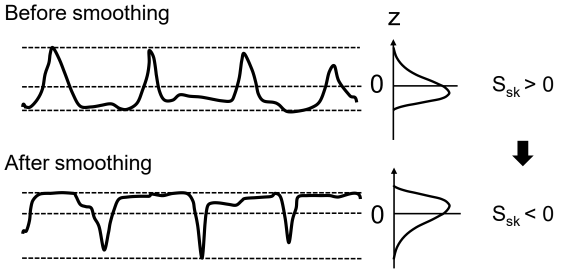

Figure 6: Schematic representation of surfaces characterized by S_{sk} values.

The figure illustrates the smoothing mechanism for a removal of the peaks, which leads to a surface with predominantly valleys. It should be mentioned, however, that the turnover of the S_{sk} values around 0 in connection with the figure only represents a trend and should always be analyzed in connection with other surface parameters. One such surface parameter is the S_{ku} value, which indicates the steepness of the amplitude density distribution. In contrast to the previously analyzed S_{sk} parameter, S_{ku} not only determines if the surface is evenly distributed, but also the sharpness that the surface artifacts themselves exhibit. Sharp surfaces represent a kurtosis value above 3, while low frequency wavy surfaces have values below 3. The calculation is based on a normal distribution of the amplitude density distribution with a value of 3. The parameter is calculated as described in the following.

$$S_{ku} = \frac{1}{s_q^4}\frac{1}{A}\iint_A z^4(x,y)\; dxdy$$

Figure 7 shows the surface parameter S_{ku} (kurtosis) of the height distribution of the smoothed and unsmoothed surfaces in relation to the build angle.

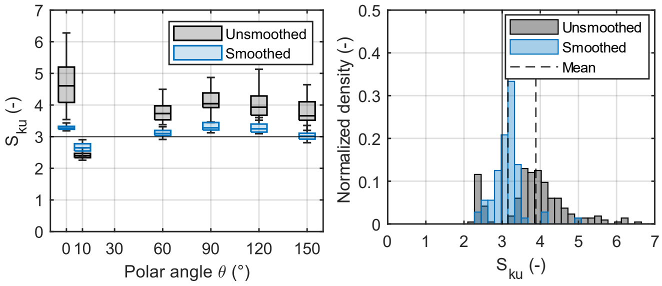

Figure 7: Kurtosis of the height distribution (S_{ku}) of unsmoothed and smoothed surfaces in relation to the build angle (left) with the corresponding data distribution (right).

A rather homogeneous distribution of unsmoothed surfaces with S_{ku} values around a mean of 4 can be observed from the boxplot. The highest value is formed by the 0° surfaces, while the lowest value is observed at the 10° surface with $S_{ku} = 2.4$. Therefore, chemical smoothing results in a reduction of all polar angles except for the 10° surface. It should be noted that not only an absolute reduction in values is achieved, but also a significant reduction in the standard deviation of data. This is further evident when considering the histogram. Overall, the S_{ku} value of the smoothed surfaces approaches the value of 3 which indicates the formation of a uniform surface character with a normal distribution of the amplitude density. Figure 8 shows a schematic representation of the kurtosis value around the threshold $S_{ku} = 3$.

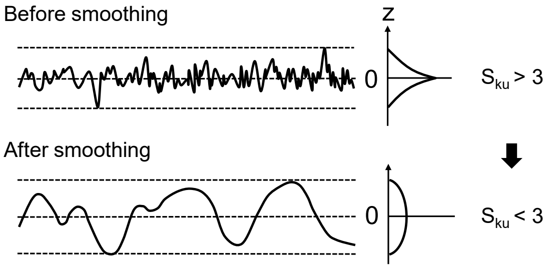

Figure 8: Schematic representation of surfaces characterized by S_{ku} values.

Until this point, the surface has been described by parameters providing information about height values and their corresponding distributions. Another valuable parameter for describing technical surfaces is the developed interfacial ratio S_{dr}. The parameter describes the ratio between the ideal projected surface area and the actual increased surface formed by peaks and valleys. Figure 9 shows the developed interfacial ratio in relation to the build angle and distribution of data.

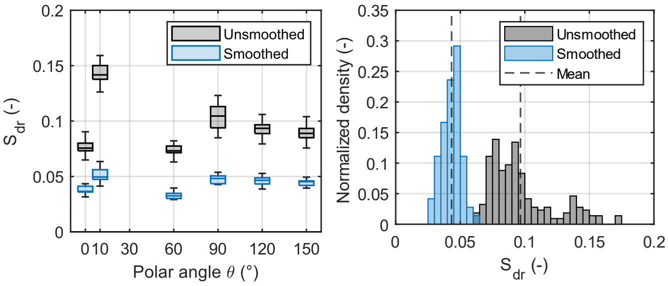

Figure 9: Developed interfacial ratio of the height distribution (S_{dr}) of unsmoothed and smoothed surfaces in relation to the build angle (left) with the corresponding data distribution (right).

The results are consistent with the observations of the root mean square height S_q, which also exhibits a peak at a polar angle of 10°. On average, the interfacial ratio of the unsmoothed surfaces is approximately 0.1, representing a 10 % increase of the calculated area in respect to the projected area. Chemical smoothing reduces this ratio by half to just below 5 %. Additionally, the deviation between individual polar angles is reduced, indicating a more homogeneous distribution.

In summary, it can be said that the developed measurement methodology shows a significant reduction in all surface parameters investigated. Particularly, the reduction observed in the 10° range is crucial for achieving a more homogeneous surface after smoothing, as shown by the mean squared height S_q. The analysis of height distribution by investigating the skewness demonstrates a shift in S_{sk} values below 0, indicating a removal of peaks and a transition towards a valley-dominated surface. Additionally, the investigation of kurtosis reveals a significant reduction in values, approaching a value of 3, which describes a normally distributed height distribution. The schematic representation of the decrease in S_{ku} values highlights the trend towards a more undulating surface. Finally, the examination of the developed interfacial ratio S_{dr} demonstrates a reduction of the actual surface area due to the elimination of peaks from 10 % to 5 %. Consequently, a surface that appears more homogenous across all polar angles can be accurately described using the developed measurement methodology. The ability to measure a variety of polar angles is particularly important to transfer statements from the methodology to actual components. The investigations reveal significant differences, notably between the areas spanning 0° in the upskin and 150° in the downskin, which cannot be detected without the given angle resolution.

5. Discussion

The development of an advanced measurement strategy for assessing surface quality in AM has been a crucial research area in the AM industry. This is attributed to the directional dependence of the resulting surfaces, necessitating areal measurements instead of tactile ones. Besides the test specimens outlined in standards, numerous geometries and studies described in literature reflect the complexity of the characteristics under investigation. A basic test specimen for the assessment of surface quality is specified in ISO/ASTM 52902. However, the geometry does not cover the needs for surface quality assessment on an industrial scale. This is due to the large number of factors influencing the process, such as the polar and azimuth angles described above. The test specimen developed in this study challenges the current state of the art and builds on the earlier research work of Grimm et al. [13]. The specimen combines the requirements of achieving a high level of detail for determining angle dependencies while simultaneously ensuring efficiency in manufacturing and measuring. The design prioritizes minimal volume without requiring support structures for polymer and metal. Furthermore, the specimen features good accessibility due to its nearly spherical shape and can be used over multiple post-processing steps without disassembly. This is a crucial requirement in the investigation of post-processing methods, as disassembling the test specimen can alter the interaction of the post-processing mechanism on the surface during before and after measurements. The number of features being investigated is directly related to the complexity of visualizing the corresponding data and the measurement effort involved. This consideration is essential when planning a large-scale measurement series.

6. Conclusion and Future Work

Additive manufacturing as a tool for production provides several process specific characteristics with advantages and restrictions. The current progress towards series applications, OEMs, and a supplier network across a range of industries underlines the need for process qualification and monitoring solutions. Determining the surface quality of parts is a standard approach to verify specifications. However, tactile surface roughness measurements are of limited use when investigating AM parts. 3D areal measurements offer added value due to a direction-independent recording of the surface. This study presents a new specimen for surface roughness measurements based on the current state of the art. The focus is particularly on efficient measurability with a high level of detail and an economical production. It has been demonstrated that an efficient analysis of a post-processing method can be conducted using the methodology, providing insights into mechanisms of the respective technology. In the future, a deep understanding of various surface parameters and their sensitivity to process parameters represents a promising perspective. To keep up with the increasing level of the associated effort of such measurements, automation solutions are crucial. The development of such solutions in collaboration with AM users is therefore key to further advancing the methodology presented.

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