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Post-processing of surface topography data for as-built metal additive surface texture characterisation

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Abstract

Surfaces of additively manufactured metal parts from powder-based processes typically show powder particle agglomerations and other features, resulting in high surface roughness. Proper characterisation of those surfaces is necessary in order to assess part quality with respect to coatability, mechanical performance or corrosion resistance for use in aerospace, automotive, medical and more industrial applications. Optical surface texture measurement allows for collection of areal surface data, while the established contact stylus method only captures line profile data. When applying optical methods for surface topography measurements, proper data acquisition and post-processing in order to assess surface texture may be complex. A number of variables can be adjusted, such as measurement settings, approaches to outlier removal, evaluated area size or form removal. This work shows the influence of selected z-range prior to measurement and the influence of choosing pre-defined outlier removal settings in MountainsMap 9.2 on selected ISO 25178-2:2022 parameters calculated from data obtained from confocal microscopy for as-built Ti6Al4V from laser powder bed fusion. The aim is to show the impact of variation in measurement and post-processing on calculated surface texture parameters and stress the importance of proper documentation in order to achieve reproducibility of data for quality management.

Keywords: Metal Additive Manufacturing, Laser Powder Bed Fusion, Surface Texture Characterisation, Optical Metrology, Confocal Microscopy.

1. Introduction

The application of metal additive manufacturing in various fields requires new approaches to quality assurance. With regard to fatigue performance, measurement of the surfaces and characterisation of surface texture are of interest.

Surfaces from laser powder bed fusion (LPBF) typically exhibit agglomerations of attached powder particles (Fig. 1) of different size and shape are typical for these surfaces and this special nature imposes new challenges on measurement systems and their application.

The stylus method is still most commonly applied in industry and has the advantages of easy application and full standardisation. It is, however, a contact method, meaning, that damage to the surface is possible. Looking at LPBF, the stylus tip movement may be restricted by particle agglomerations during measurement due to resulting undercuts and high slopes (see Fig. 1).

In recent years, optical measurement systems are gaining acceptance. They offer non-contact measurements with representative areal coverage and enable application of areal surface texture characterisation. Optical measurements and post-processing of data are not yet standardised. However, a number of methods are listed in ISO 25178-6 [7] as suitable methods for characterisation of areal surface texture and the standard is continuously updated.

When specifically considering laser scanning confocal microscopy (LSCM), large spikes can be observed (see Fig. 3) in the data having a significant influence on typically used areal parameters such as *Sa* (arithmetic mean height), *Sq* (root mean square height) or *Sz* (maximum height), as these depend exclusively on height values and are hence very sensitive to local extremes.

Information on data acquisition and processing, such as outlier removal, reduction of measurement noise or levelling is often missing in studies on AM surface texture characterisation [11, 13]. However, where areal methods are applied, this information is crucial for reproducibility, since those processing steps can heavily influence the result.

This work aims at showing the impact of selected measurement and post-processing settings on surface texture parameters and stressing the importance of proper documentation of data acquisition and post-processing steps. The effects of changing the z-range for the measurement, the outlier removal setting and interpolating non-measured points (NMP) on *Sq* (root mean square height), *Sz* (maximum height), *Sk* (core height) and *Svk* (reduced valley depth) are discussed.

2. Material and methods

2.1. Laser Scanning Confocal Microscopy

In laser scanning confocal microscopy (LSCM), the surface is scanned by a laser in different focal planes, only exposing the area portion in focus. The 3D surface representation is created by layering data across the focal planes [8]. The method is line-of-sight, meaning that re-entrant features, shown in Fig. 1, cannot be detected.

The used instrument in this study is the Keyence VK 9700 with the 20x magnification lens, achieving a spatial resolution of 0.69 µm. Measurement uncertainty is not included in the presented results. An overview of data acquisition and processing steps is given in Fig. 2. In ISO 25178-6 [7], the method is listed as suitable method for areal surface texture characterisation. Details on measurement and post-processing are not yet included in the standard. Taking a look at literature, the method is mainly used for areal surface texture characterisation and high-resolution imaging [2, 5, 10, 12].

2.2. Data Sets

The evaluated data sets originate from a Ti6Al4V sample in as-built condition from LPBF (Fig. 1). Typical powder particle agglomerations of different sizes are visible in scanning electron microscopy (SEM) images. Both data sets show an identical, randomly chosen location on the sample and the only difference in measurement settings is the predefined z-range the confocal microscope. One measurement was taken with a z-range of 229 µm, the second with 368 µm. The first value was selected based on the surface topography; the second value resulted from increasing the z-range in positive direction to study its effect.

When only looking at an individual image, it may be unclear why the effect of increasing z-range is interesting. However, when measuring larger surface portions requiring stitching of multiple images, the z-range for the used instrument (Keyence VK 9700, lens with 20x magnification) has to be set according to the highest height variation to be detected.

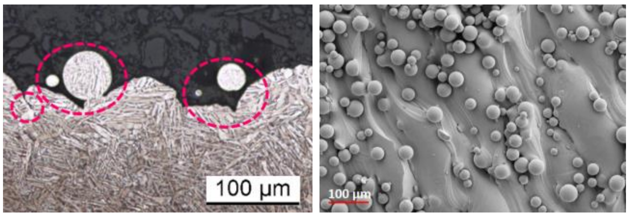

Fig 1. Powder particle agglomerations on as-built Ti6Al4V surfaces from LPBF: Cross section micrograph, illustration of undercuts *(left)*, SEM showing agglomerations of different sizes and underlying waviness *(right)*.

2.3. Surface Data Evaluation

The data evaluation was performed using MountainsMap® version 9.2. The raw data from confocal microscopy was imported and outlier removal 'soft', 'normal' and 'strong' was applied for the two evaluated data sets. The MountainsMap® outlier removal algorithm uses median filters (of variable size according to setting) to smooth isolated outliers and removes outliers around edges and converts them into non-measured points (for increased strength, more points are removed).

In order to quantify the influence of the chosen variations, the ISO 25178-2 parameters *Sq* (root mean square height), *Sz* (maximum total height) *Sk* (core height) and *Svk* (reduced valley depth) are compared amongst the post-processed data set versions. *Sq* and *Sz* are frequently applied in industrial environments while *Sk* and *Svk* are less common. The latter are calculated from the material ratio curve and were found to have potential for metal AM surface texture characterisation in previous studies by the authors [3, 4].

Prior to the parameter calculation a Gaussian S-filter of 2.5 µm and a Gaussian L-filter of 0.5 mm was applied to the processed surface data. The steps taken are summarised in Fig. 2.

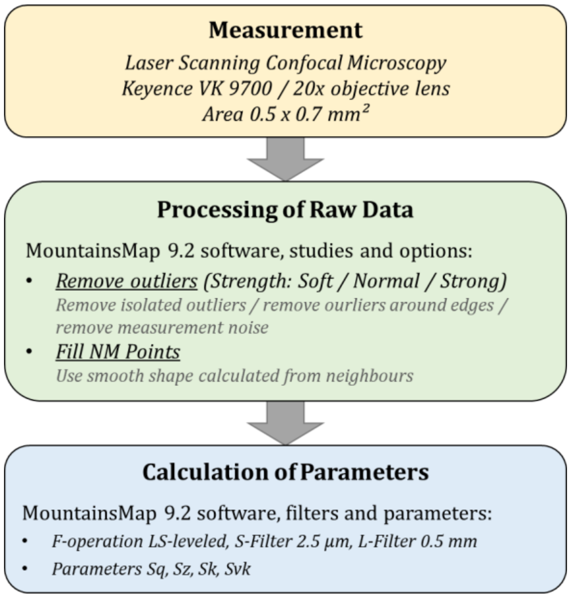

Fig 2. Measurement, data processing and evaluation steps; Studies, options, filters and parameters selected in MountainsMap 9.2

3. Results and discussion

Typical confocal microscopy raw data of LPBF surfaces show large spikes (see Fig. 3, also refer to [11]), that occur around the edges of powder particles. Comparing the raw data to the microscopic images (i.e., Fig. 1) clearly shows these spikes are not physically present on the measured surfaces. The spikes are artefacts arising during data acquisition with the laser scanning confocal microscope.

A likely origin of the spikes are particle agglomerations, which are LPBF specific surface features. Confocal microscopy is a line-of-sight method and as-built LPBF surfaces show undercuts (see Fig. 1), which cannot be detected. On the boundaries of attached particles, the instrument detects two signals, one from the boundary and one from the surface below, leading to the display of a spike artefact. Furthermore, it is observed, that the spherical shapes of the powder particles are not accurately depicted, which is a known phenomenon in confocal microscopy [1, 12, 14].

From previous measurement results it could be observed that the spikes have the size of the measured z-range. Fig. 3 shows measurements at identical location with variation of the pre-set z-range. The raw data illustration confirms the assumption that the size of the artefact does not depend on the size of surface features but is mostly defined by the measurement setting.

The following main aspects were considered in the data evaluation:

- Effect of increasing the measured Δz.
- Effect of outlier removal and fitting non-measured points.

3.1. Raw Data with Different Δz

Looking at the chosen parameters, there is a significant difference between the Δz = 229 µm and Δz = 368 µm data sets. As expected, the largest deviation can be observed for the extreme value *Sz* (maximum total height), namely 40%. Note that due to filtering the data to separate roughness from waviness components (L-filter 0.5 mm), the value is smaller than the maximum measured z-range of the respective data sets.

Smaller but still significant is the difference of the root mean square height *Sq*, which amounts to 39%. This shows that *Sq*, being a parameter that is supposed to characterise the overall surface quality [4], is very sensitive local extreme values, which are in this case caused by the measurement setting.

Considering the selected parameters from the material ratio curve, the difference is relatively low, namely 12% for the core height *Sk* and 4% for the reduced valley depth *Svk* and hence react less sensitively to the size of the spike artefacts.

Table 1 summarises the above-mentioned numerical values. When comparing the surface texture parameters for both data sets it is also notable, that while all other values increase with increasing Δz, *Svk* decreases slightly. This is possibly due to the spikes creating an increased number of data points, not only in the peak, but also in core portion of the profile, resulting in a slightly flatter main slope. Since the z-range in this case was only extended in positive direction ('peak portion'), the effect on the valley parameter is small. For detailed information on the material ratio curve parameter calculation, please refer to [4, 9].

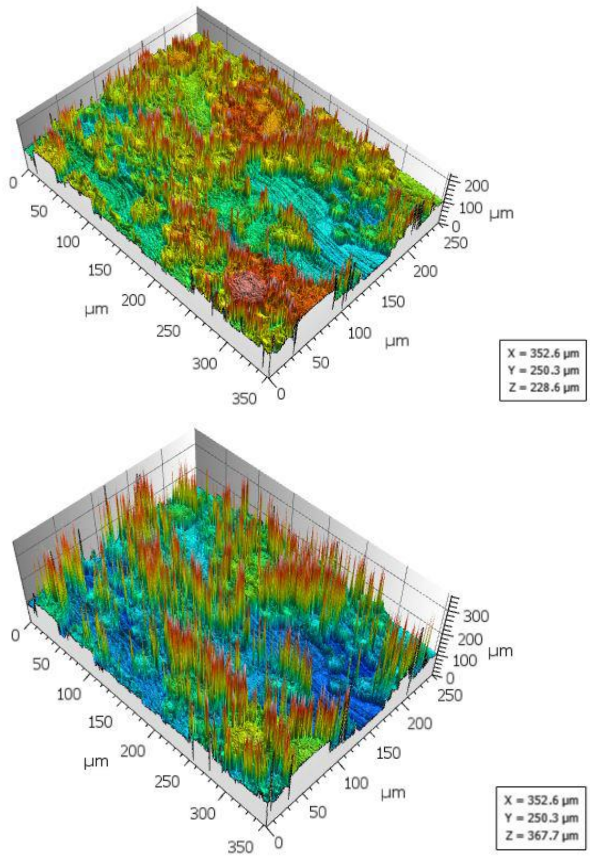

Fig 3. Spikes in confocal raw data of as-built Ti6Al4V. Top and bottom images show identical locations on the surface with different Δz setting.

Table 1. ISO 25178 parameters for Δz = 229 µm and Δz = 368 µm (S-filter 2.5 µm, L-filter 0.5 mm).

Parameter	*Δz = 229 µm*	*Δz = 368 µm*	*Deviation*
Sq / µm	24.38	39.83	39%
Sz / µm	191.40	320.80	40%
Sk / µm	59.54	67.44	12%
Svk / µm	14.31	13.78	-4%

These results clearly show the necessity of properly post-processing data from confocal microscopy (and other optical methods) in order to mitigate the effect of measurement artefacts.

Previous round-robin testing on best-practice measurement and characterisation of surface texture with different labs has shown that some users are unfamiliar with how to choose post-processing settings for raw data from optical measurement, which supports the previous statement.

3.2. Outlier Removal and Non-measured Points

Depending on the chosen strength of the applied outlier removal, the non-measured points (NMP) amount to roughly 15% for the setting 'soft', 20% for 'normal' and 30% for 'strong' for both data sets.

In general, a trend of lower parameter values for stronger outlier removal can be observed (Table 3). The strongest effect is on *Sz*, since with removing more spikes, more extreme values are eliminated. When removing a spike, it is usually eliminated starting from its root, which is why there are data points missing within the core part of the profile, as visible in Fig. 4 and Fig. 5, causing differences in *Sk*, *Svk* and *Sq*.

Table 2. Non-measured points, dependence on outlier removal strength and Δz

Data Set / Outlier Removal	***Δz = 229 µm***	***Δz = 368 µm***
Soft	15.55%	14.52%
Normal	20.15%	19.20%
Strong	31.75%	30.08%

Table 3. Resulting ISO 25178 parameters for variation of outlier removal strength and fitting non-measured points for Δz = 229 µm.

	Soft	**Normal**	**Strong**
Sq (NMP) / µm	22.85	22.81	22.54
Sq (NMP filled) / µm	22.63	22.44	21.88
Deviation	1%	2%	3%
Sz (NMP) / µm	186.40	184.00	170.80
Sz (NMP filled) / µm	186.40	184.00	170.80
Deviation	0%	0%	0%
Sk (NMP) / µm	55.26	55.15	54.36
Sk (NMP filled) / µm	54.58	54.03	52.60
Deviation	1%	2%	3%
Svk (NMP) / µm	13.42	13.05	11.86
Svk (NMP filled) / µm	14.18	13.98	13.16
Deviation	-6%	-7%	-11%

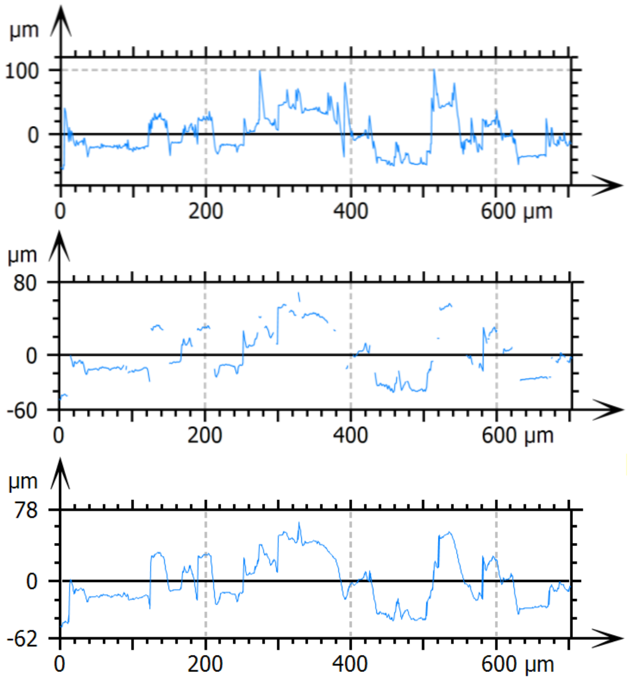

Fig 4. Profiles extracted from Δz = 229 µm data set: Original (top), after outlier removal with NMP 17.8% (middle) and with interpolated NMP (bottom)

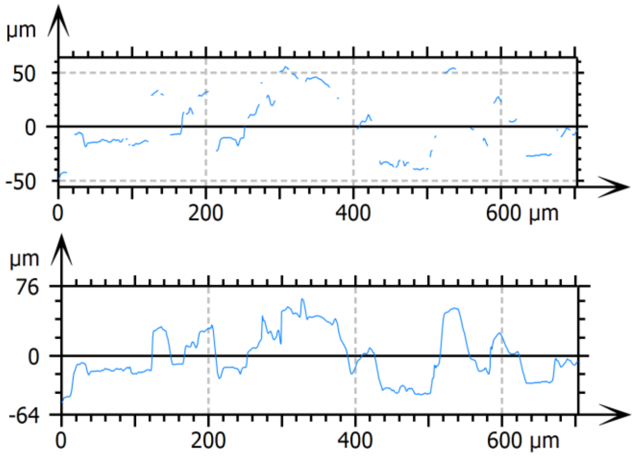

Fig 5. Profiles extracted from Δz = 229 µm data set: After outlier removal with NMP 29.5% *(middle)* and with interpolated NMP *(bottom)*

3.3. Interpolation of Non-measured Points

Filling the NMP with interpolated values causes a variation of parameter values of up to 11% for Δz = 229 µm and 12% (Table 3) for Δz = 368 µm. The parameter *Sz* is not affected by the interpolation.

This issue can be illustrated by looking at an extracted profile with nearly 18% NMP and interpolated points in Fig. 4. After the outlier removal step, data is mainly missing in the core portion (close to the centre line) of the profile. The material ratio curve is hence gaining core material when interpolating NMP, resulting in flattening the curve (more data points per height level), which causes a slight decrease of *Sk* and a slight increase of *Svk*. Fig. 4 and Fig. 5 clearly show the difference between 'normal' and 'strong' outlier removal. The interpolated curve in Fig. 4 still shows some sharp edges while Fig. 5 is relatively smooth.

4. Conclusions

The presented data show that changing measurement settings and use of different post-processing options can cause a large variation on surface texture parameters (up to 40%). Many publications do not state the applied steps. In addition, round-robin testing, where metal additive surface measurement and characterisation were compared, showed that there are users who are unfamiliar with post-processing of raw data from optical measurements. In order to ensure reproducibility of results, specification, documentation and standardisation are essential.

Outlier removal and interpolation of non-measured points may have a significant effect on the resulting parameters. Outlier removal settings have the strongest impact on the extreme value *Sz*. Filling in NMP does not alter *Sz* but does have an influence on the material ratio curve parameters *Sk* and *Svk* and the root mean square *Sq* due to the addition of data points in the core portion.

When choosing the appropriate setting for outlier removal for one's confocal microscopy data, it is recommended to take a look at the 3D view to check the spikes' size and quantity. The authors will mostly use the 'soft' or 'normal' setting in MountainsMap 9.2, to keep as much of the measured data as possible while getting rid of the artefacts.

The NMP interpolation, although adding points that were not measured may distort the results, is considered a valid approximation, since the measured surface is continuous.

Due to the large number of settings to be varied, the strong impact of their modification and lack of standardisation, the application of optical measurement systems requires a high level of expertise.

A major advantage of confocal measurements and other optical systems is the areal coverage, allowing for three-dimensional data acquisition (with the limitation to line-of-sight) rather than just a single profile as attained from the stylus method. This does not only accommodate a better representation of the surface from a statistical point of view, but also enables the characterisation of process-specific surface features, such as powder particle agglomerations in LPBF.

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Author's statement

Conflict of interest: Authors state no conflict of interest. Informed consent: Informed consent has been obtained from all individuals included in this study. Ethical approval: The research related to human use complies with all the relevant national regulations, institutional policies and was performed in accordance with the tenets of the Helsinki Declaration, and has been approved by the authors' institutional review board or equivalent committee.

Data availability

The data is available from the corresponding author upon request.

Author contributions

Conceptualisation, T.B.; methodology, T.B.; formal analysis, T.B.; investigation, T.B., H.B. and M.A.; data curation, T.B.; writing—original draft preparation, T.B.; writing—review and editing, T.B., H.B. and M.A.; visualisation, T.B.; funding acquisition, H.B. and M.A.; All authors have read and agreed to the published version of the manuscript.

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