FOCUS VARIATION MEASUREMENT OF METAL ADDITIVELY MANUFACTURED SURFACES

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INTRODUCTION

Metal additive manufactured (AM) surfaces produced via powder bed fusion (PBF) feature complex and irregular topographies and significant variations depending on build orientation [1–3]. Top surfaces contain traces of the laser or electron-beam melting scan path, as well as sparse spatter formations created during the processing of the layer. Side surfaces are the result of layer-upon-layer stacking and feature attached, partially melted or unmelted particles [3,4]. When measured with optical instruments, PBF surfaces present significant challenges related to disuniformity of optical properties, with highly reflective smooth regions appearing together with poorly contrasted, dark recesses, high aspect-ratio features, high slopes and undercuts [2,5]. Amongst optical surface topography measurement technologies, focus variation (FV) offers a good compromise between quality of measurement results, ease of operation and required measurement time [6,7]. Thus, FV has often been used for the measurement of metal AM surfaces [2,3,8–10]. Because of the widespread adoption of FV instruments for the measurement of metal AM surfaces, further research is required to improve our understanding of how the FV technology behaves when applied to such surfaces, with the final aim of identifying guidelines showing how FV instruments should be configured for optimal operation for AM. Similar research is being performed for coherence scanning interferometry [5] and other instruments. To ensure generality of the results, the experiments are performed on a variety of materials and metal powder bed fusion (PBF) processes. The measurements were performed using an Alicona InfiniteFocus (IF) G5 instrument, but the findings should apply to any standard FV instrument [11].

METHODOLOGY

Four samples were considered. Three were produced by laser powder bed fusion (LPBF, Renishaw AM250) and one by electron PBF (electron beam melting (EBM) Arcam A2X). Both the top and side (vertical) surfaces of the samples were considered for the analysis. For the material of the samples, Al-Si-10Mg, Inconel 718 and Ti-6Al-4V were used for LPBF, Ti-6Al-4V for EBM.

Measurement

The considered measurement process parameters were: magnification (10×, 20× and 50× objective lens); type of illumination (coaxial, polarised coaxial and ring light); desired, reference lateral resolution (a variable introduced by the instrument manufacturer that indirectly controls the lateral sampling distance [12] and ultimately affects the actual lateral resolution of the measurement); and vertical resolution (a variable that controls the vertical spacing between subsequent images taken during vertical scanning, where the images are then used to compute the local surface height values through detection of maximum contrast [7,8]). Lateral and vertical resolution levels were chosen by considering the default values suggested by the instrument control software at each magnification, plus one or two additional levels also chosen within the range of acceptable values suggested by the instrument software. From each one of the four samples, two regions were selected, one on the top surface, the other on one of the sides. Over each region, three replicate measurements were performed in sequence, under repeatability conditions (i.e. same set-up and position of the objective over the region), leading to a total of twenty-four measurement per set-up. A total of sixty-three set-ups were investigated, considering the combinations of measurement control parameters illustrated in Table 1, leading to a grand total of 1512 measured datasets.

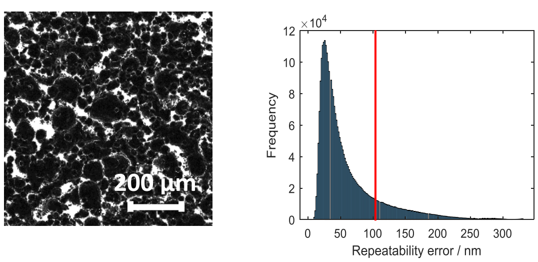
TABLE 1. Selected FV measurement process parameters and their values

Objective lens magnification	10× (NA 0.3 FoV (1.62×1.62) mm)	20× (NA 0.4 FoV (0.81×0.81) mm)	50× (NA 0.6 FoV (0.32×0.32) mm)
Type of illumination	Coaxial Polarised coaxial Ring light	Coaxial Polarised coaxial Ring light	Coaxial Polarised coaxial Ring light
Lateral resolution / µm	2, 4	1, 2, 3	1, 2
Vertical resolution / nm	100, 300, 900	50, 200, 500	20, 50, 200

Measurement quality indicators

Each measurement performed with FV instrument results in a height map, an RGB colour map and a "quality" map (map of local repeatability error). The following were considered as quality indicators:

- the upper quartile (Q3) of the distribution of repeatability errors, as extracted from the quality map (as shown in Figure 1);
- the percentage of non-measured points in the height map (NMP);and
- the areal surface texture field parameter *Sa* (arithmetical mean height) from the standard ISO 25178-2 [13].



(a) (b)

FIGURE 1. Computation of upper quartile of repeatability error (Q3); a) quality map from the measurement of one of the metal additive surfaces; b) probability distribution of repeatability error (upper quartile indicated in red)

Data generation and analysis

For each measurement region and for each magnification, three independent, general full factorial designs of experiments (DOE) were generated for Q3, NMP and *Sa* respectively, to determine the sensitivity of the quality indicators to the factors: type of illumination, vertical resolution and lateral resolution (with levels as previously illustrated in Table 1). From each DOE, regression models were fitted, and results were investigated by looking at the main effects plots and statistical significance through ANOVA.

RESULTS

Visual inspection

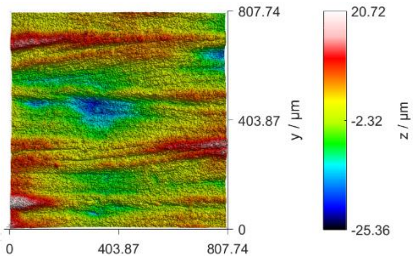
Visual inspection of the height maps and RGB maps was used to assess whether changing measurement control parameters would induce visually appreciable alterations in the reconstructed topographies.

The most evident result of observing at different magnifications is that a different range of topographic scales are captured: for the test cases, lower magnifications allowed capturing of a larger number of weld tracks, as well the underlying large-scale waviness often present on top surfaces [2]. Higher magnifications allowed the acquisition of smaller-scale features such as weld ripples [4]. Several surface features were visible at all magnifications (e.g. medium-sized spatter formations), albeit represented by slightly different topographic content in the spatial frequency domain. However, such differences were usually not clearly appreciable by simple visual assessment.

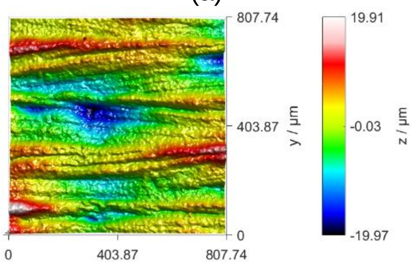
Changes in the vertical resolution also did not produce visually appreciable alterations in the reconstructed height maps.

On the contrary, changing lateral resolution produced a visible effect in the reconstructed height maps (Figure 2). Despite the size of the measured area remaining the same, improved lateral resolutions (smaller lateral resolution values) led to increased visibility of small-scale, topographic features. On the contrary, worse resolutions led to loss of small-scale detail, visually similar to applying a smoothing effect to the topography.

Changes of illumination type were primarily appreciable by looking at the RGB maps resulting from measurement (Figure 3). The RGB maps contain pixel information used to compute



(a)



(b)

FIGURE 2. Effects of changing lateral resolution: *height map visualisation of EBM titanium alloy top surface measured using 20× magnification, coaxial light, vertical resolution at 200 nm, and lateral resolution at (a) 1 µm and (b) 3 µm*

maximum contrast by the FV technology during vertical scanning: it is, therefore, expected that changes in the RGB maps may also correspond to changes in the height maps. However, as shown in Figure 3, despite the RGB maps appearing different, a similar level of discrepancy was not equivalently visible on the associated height maps, albeit differences in height ranges were undeniably present as shown by the height ranges reported in the associated colour bars.

Quality of model fitting

The determination coefficient (R^2) of the regression models for Q3 was above 80% in almost all cases, showing good fitting overall. On the contrary, the regression models for NMP were characterised by poor fitting so results could not be considered as particularly reliable. R^2 was above 85% in all cases for the models for the surface texture parameter *Sa*.

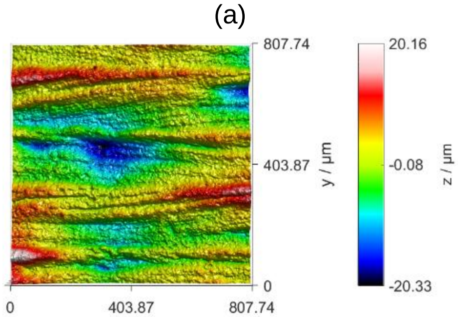
ANOVA and main effects plots

Vertical resolution: vertical resolution was always significant $p<0.05$) for Q3, with improved resolutions (smaller values) leading to lower Q3 values as shown in Figure 4. However, improved vertical resolutions (larger values) also led to higher NMP (Figure 5). From the ANOVA there was not enough evidence to confirm the influence of vertical resolution on *Sa*.

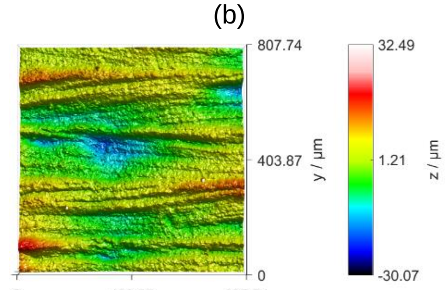
Lateral resolution: improved lateral resolutions (smaller values) generally led to higher NMP, whilst there was not enough evidence from the ANOVA to confirm the influence of lateral resolution on Q3. Worse lateral resolutions (larger values) also usually led to smaller *Sa* values, because of larger resolution values acting as a low-pass filter, i.e. introducing a smoothing effect in the reconstructed topography. In a few

(a)

(b)



(c)



(d)

FIGURE 3. Effects of changing illumination type: EBM titanium alloy top surface measured using 20× magnification, lateral resolution at 2 µm, vertical resolution at 200 nm; focus stacked RGB images using (a) coaxial light and (b) ring light illumination. Corresponding height maps using (c) coaxial light and (d) ring light illumination.

cases (some side surfaces at higher magnifications), the trend was inverted, presumably because of *Sa* being influenced by individual features covering a higher percentage of the field of view.

Illumination type: The ANOVA was inconclusive regarding the effects of type of illumination on Q3 and NMP, except at 10× magnification, where usually smoother surfaces (top surfaces) benefitted more from ring light illumination (lower NMP). The influence of type of illumination on the *Sa* parameter was consistently observed. Usually, ring light illumination led to lower *Sa* at lower magnifications (10×, 20×), as shown in Figure 6. A not-so-consistent trend was observed at 50×, possibly because of individual features occupying a significant percentage of the field of view.

DISCUSSION

Within this work, surface topographies ranging from smoother to rougher, from highly reflective to poorly reflective, and from low to high aspect-ratios were covered. It is, therefore, reasonable to assume that surfaces originating from different manufacturing processes, but ultimately similar in terms of topographic complexity and optical properties, may lead to similar behaviour of the FV technology.

The results presented in this work indicate that the choice of FV measurement control parameters does indeed affect FV measurement performance and behaviour. However, one of the most interesting results is that the values of parameters such as *Sa* are consistent across measurement set-ups. This is comforting as it suggests that FV can be used to measure metal additive surfaces with comparable results across multiple measurement set-ups. If one focuses on the actual topographic detail obtained from reconstruction though, it is not possible to say whether the metrological quality of the reconstructed topographies (in particular in terms of accuracy) is better or worse in some set-ups versus others. This is because neither NMP nor Q3 are suitable indicators for accuracy, and comparison with a more accurate reference is needed. Previous work on the generation of statistical topography models from repeated measurements [4,8] indicates a possible pathway to approach the issue, although measurement results from a higher-accuracy instrument are still needed. In general, the challenge of understanding how uncertainty should be computed and associated to surface topography characterisation is currently unsolved [14].

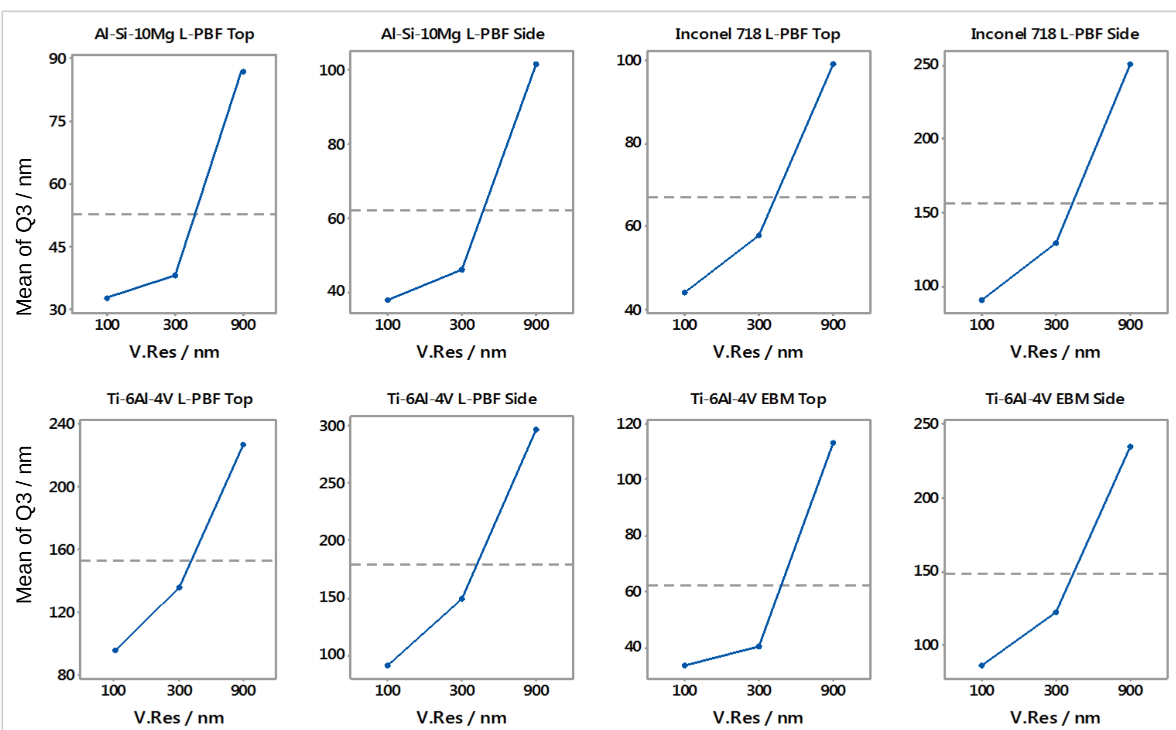


FIGURE 4. Main effect plots of vertical resolution on Q3 at 10× magnification ($p<0.05$ for all the plots).

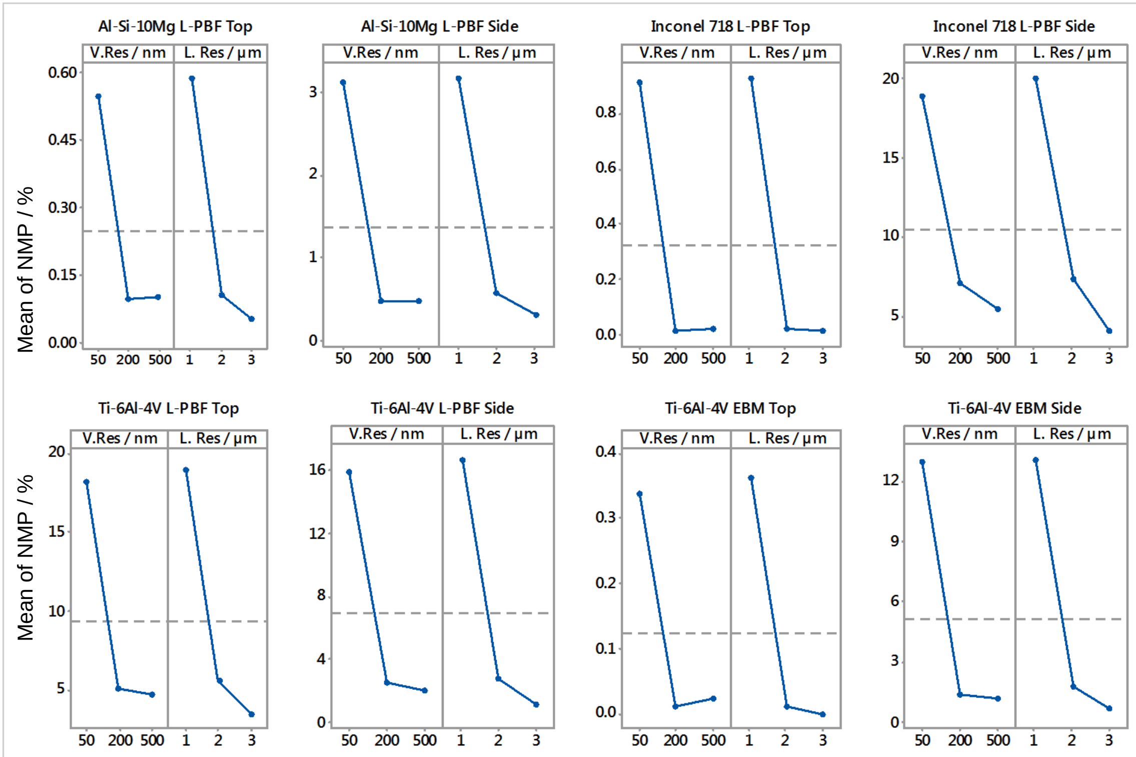


FIGURE 5. Main effect plots of vertical resolution on NMP at 20× magnification ($p<0.05$ for all the plots).

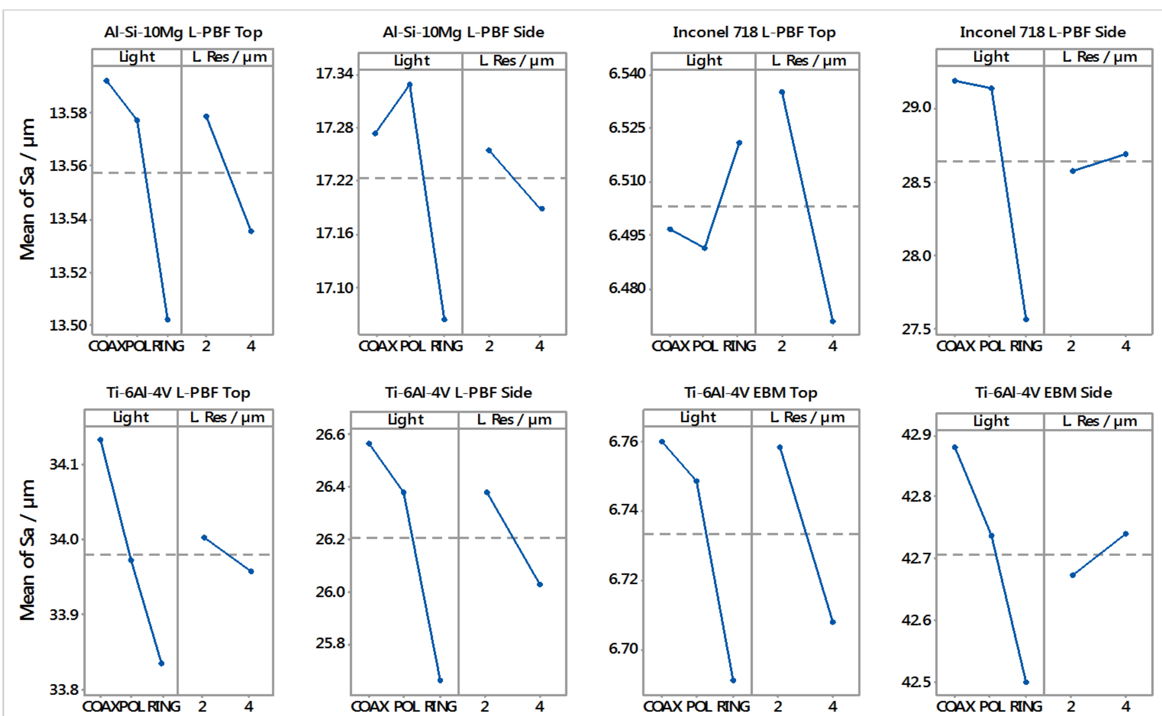


FIGURE 6. Main effect plots of vertical resolution on Sa at 10× magnification ($p<0.05$ for all the plots).

CONCLUSIONS

Metal additive surfaces, produced by PBF processes, present a wide array of topographies, each with their own specific measurement challenges. Despite such variability, some general conclusions have been drawn. The computation of surface texture parameters such as *Sa* (ISO 25178-2 [13]) is mostly unaffected by measurement set-up. However, other indicators such as local repeatability error in height determination and the percentage of non-measured points are significantly affected by the control parameters, although the trends vary with surface type.

FV measurement is a technology with plenty of opportunity for the measurement of complex surfaces, such as those produced by metal AM. Despite the technology being relatively easy to use, there are many parameters that could be changed by an operator leading to different measurement outcomes. Further research, based on the availability of more accurate measurements to act as references, is needed to understand whether such changes represent improvements or not.

AKNOWLEDGEMENTS

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