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Detailed evaluation of topographical effects of Hirtisation post-processing on electron beam powder bed fusion (PBF-EB) manufactured Ti-6Al-4V component

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ABSTRACT

Metal additive manufacturing surface topographies are complex and challenging to characterise due to e.g. steep local slopes, re-entrant features, varying reflectivity and features of interest in vastly different scale ranges. Nevertheless, average height parameters such as Ra or Sa are commonly used as sole parameters for characterisation. In this paper, a novel method for selecting relevant parameters for evaluation is proposed and demonstrated using a case study where the smoothing effects after three processing steps of the electro chemical post-process Hirtisation of a metal AM surface are quantified. The method uses a combination of conventional areal texture parameters, multiscale analysis and statistics and can be used to efficiently achieve a detailed and more relevant surface topography characterisation. It was found that the three process steps have different effects on the surface topography regarding the types and sizes of features that were affected. In total, Sdq was reduced by 97 %, S5v was reduced by 81 % and Sa was reduced by 78 %. A surface texture with much lower average roughness, less deep pits and less steep slopes was produced, which is expected to be beneficial for improved fatigue properties.

1. Introduction

Metal additive manufacturing (AM) are manufacturing methods that offer great freedom of design and the ability to produce near net shape components regarding geometry. As with any other manufacturing method, AM produced parts need to fit in assemblies and meet functional requirements regarding both geometry and surface integrity [3]. For many applications, post-processing is necessary to achieve required tolerances regarding geometry and surface integrity, including surface topography [4].

Surface integrity is defined as the inherent or enhanced condition of a surface produced in a machining or other surface generating operations [5]. Surface integrity is often characterised using hardness, residual stress, surface topography, microstructural changes, corrosion resistance, etc. It entails the effects of processing on material properties on the very outer part of the surface (on-surface properties), or directly under the surface (sub-surface properties). Properties which often have a significant impact on a component's functional performance [6]. See Fig. 1 for a simple framework for surface integrity.

The required surface integrity properties for a particular surface are determined by the required functional performance. Tolerancing of such properties is carried out at the design phase of the product realization loop [7], and has consequences in the pre-production and production phases regarding most aspects [8], see Fig. 2. Therefore, to be able to carry out any kind of functionally relevant tolerancing of surface integrity properties, some relation between function and the properties needs to be established. The relationship could be realised as a physics-based mathematical model suitable for simulations, experimentally proven functional correlations, or some other non-physics-based model [9]. In addition, a combination of modelling and statistics can be used to estimate uncertainties, which can be useful for tolerancing or for process optimization [10].

In the present paper, focus is on understanding the effects of the Hirtisation process on the on-surface integrity properties of an electron beam powder bed fusion (PBF-EB) manufactured Ti-6Al-4V component, such as surface texture and other topographical features. This is valuable information in the pre-production and production phases for tuning the manufacturing and inspection processes.

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Nomenclature

ISO 21920-2 profile parameters [1]
Ra (μm) Average mean of the profile height
Rz (μm) Average maximum height of the profile

ISO 25178-2 areal parameters [2] Field parameters
Sq (μm) Root-mean-square height
Ssk Skewness
Sku Kurtosis
Sa (μm) Arithmetic mean height
Sv Maximum height of valleys
Sz Maximum height of the surface
Sal (mm) Fastest decay auto-correlation rate
Str [s = 0.2] Texture-aspect ratio
Sdq Root-mean-square gradient
Sdr (%) Developed interfacial area ratio
Sk (μm) Core roughness depth
Spk (μm) Reduced summit height
Svk (μm) Reduced valley depth

Feature parameters [pruning 5 %]
Spd (1/mm^2) Density of peaks
Spc (1/mm) Arithmetic mean peak curvature
S10z (μm) Ten-point height
S5p (μm) Five-point peak height
S5v (μm) Five-point pit height

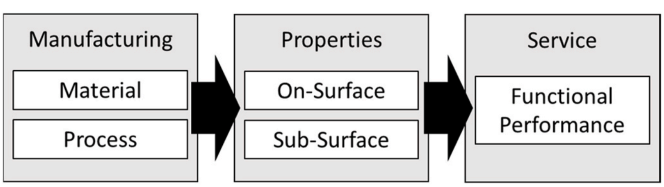

Fig. 1. Simple framework for surface integrity.

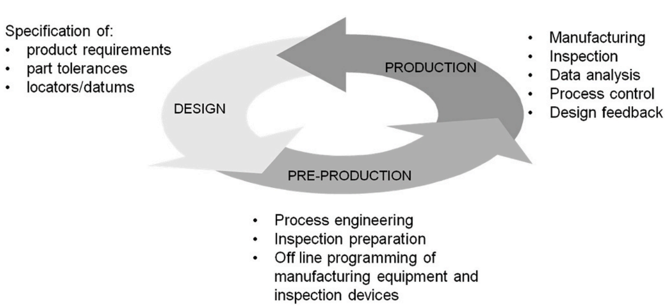

Fig. 2. Product realization loop as presented in Ref. [7], adapted from Ref. [8].

1.1. Surface integrity of AM Ti-6Al-4V components

AM with superalloys, such as Ti-6Al-4V, offers a great potential for manufacturing complex parts that are well suited for gas turbine applications, which typically are designed for low weight, high durability and high strength at elevated temperatures [11].

The PBF-EB processes, described for example by Frazier [12] and in ISO/ASTM 52900 [13], involve rapid heating, melting and rapid solidification of an alloy by successively moving a heat source in a layer by layer pattern [11]. The processes induce shrinkage as well as phase transformations which in turn may result in local residual stresses and distortions. The stresses and distortions are the result of the superimposition of spatially varied thermal gradients [14]. There are different post processes available to affect surface integrity (on-surface and sub-surface) as well as bulk properties of AM components [15]. Currently, there is a strong focus on minimising unwanted properties from the AM processes and optimising properties using post-processing.

In parts manufactured using laser beam powder bed fusion (PBF-LB) or electron beam powder bed fusion (PBF-EB), defects in the microstructure, such as pores which can act as crack initiation sites and are very important for fatigue life, can many times be observed close to inner and outer surfaces [16]. The defects can be affected by post-processes such as hot isostatic pressing or machining. Some defects close to the surface can be difficult to remove through post-processing since they can be deep or be uncovered during the post-processing [17]. For electro-chemical post-processes, such defects can result in an increased material removal rate due to the increased electrical potential in such locations that may overexpose the material regarding material removal rate compared to a flat surface [18].

One relatively newly available post-processing technique is Hirtisation which is a chemical-electrochemical process for removal of support structures and partially melted powder particles with the ability to create surfaces with low surface roughness [19]. However, few scientific studies have been published regarding the process and the effects on surface integrity properties.

The Hirtisation process is based on a combination of electrochemical pulse methods, flow and particle assisted chemical removal and chemical surface treatment. Some technical process aspects need to be considered to achieve the required surface quality, such as: Initial surface roughness, original powder quality (water content, oxidation etc.), accessibility in the flow-through case, material (the process fluids must be adapted to the material), material removal depending on the required roughness, if support structures are present, and the design of the support structures [19].

Romano et al. mentioned Hirtisation as a possible method for removal of surface material, and thereby elimination of pores near the surface, to improve the fatigue life of a PBF-LB manufactured stainless steel component [20], however, the method was not tested or evaluated.

Stelzer et al. investigated mechanical properties of PBF-LB and PBF-EB manufactured aluminium samples of SS316L, AlSi10Mg and Ti-6Al-4V after different post-processes, including Hirtisation [21,22]. The aluminium samples were shot peened before the Hirtisation process. Focus of the study was functionality of the components in terms of tensile strength and fatigue life. Surface roughness before and after surface treatment was reported using the profile parameters Ra and Rz [23]. It was found that the surface finishing process, shot peening followed by Hirtisation, reduced the surface roughness by 38 %–74 %, depending on the material and processing, and improved the functional properties of the aluminium samples [21,22].

The Hirtisation process was used to post-process PBF-EB manufactured Ti6Al4V samples for fatigue testing [24]. It was found that the post-processing reduced the surface roughness from as-built PBF-EB manufactured Ti-6Al-4V and increased the fatigue resistance. The profile parameter Ra was used for characterisation of the surface roughness.

The Hirtisation process, as well as chemical milling, was used to post-process PBF-EB manufactured Ti-6Al-4V samples [18]. It was found that both post-processes successfully could reduce the surface roughness of the samples by 67 %–74 % depending on evaluated the characterisation parameter. Surface topography was characterised using Sa, Sv and Sz. Sv was suggested as the best parameter to use among these. The difficulties of using height parameters for characterising the complex nature of the investigated surfaces were discussed in a separate section [18].

In summary, not much information has been published regarding the effects on surface integrity properties caused by the Hirtisation process in the scientific literature. Specifically, surface roughness effects have been evaluated in relatively simple terms, mostly using the arithmetical mean height of the surface, Ra or Sa, or other averaging hight parameters.

1.2. Surface texture evaluation and specification

Regarding measurement and analysis of metal AM surface texture [25], one of the on-surface properties in Fig. 1, there are still remaining challenges pertaining to obtaining high fidelity measurement data, how the data should be analysed as well as how requirements should be specified [26]. However, general guidance can now be found in a the newly published standard ASTM F3624-23 [27]. There is also specific guidance on how some process related surface features can be characterised [28]. Surface texture is commonly measured and analysed along a profile, z(x), or over an area z(x, y). Profile texture is characterised and toleranced using parameters defined in ISO 21920-2 (replacing ISO 4287) [1]. Areal texture is characterised and toleranced using parameters defined in the ISO 25178-2 standard [2]. Using areal texture rather than profile texture can give more possibilities for robust and functionally relevant characterisations [29]. Characterising, or specifying, a surface using texture parameters is done to create a parametric description that can be used to control the processing or to predict the performance of the surface. Thus, correctly used, parameters can provide a link between surface texture, its processing and function [30]. Uses can for example be improving functionality such as fatigue life [31], or appearance [32], or improving processing to produce smoother surfaces [33] or to minimise defects [34].

The parameters in the current standard for areal characterisation, ISO 25178-2 [2], were formulated to accommodate characterisation of surfaces manufactured by other methods than the comparably novel method of metal AM. Most of the parameters describe the surface in a summarising statistical way. There are also multiscale methods available with which it can be possible to perform a more complex characterisation. The term ‘multiscale analysis’ describes the process of studying topographies at multiple scales of observation (i.e. wavelengths), and comparing the findings acquired from observations at different scales [35]. Furthermore, feature based characterisations for metal additive manufacturing are under development [36] but these are not yet part of the ISO standards. Future inclusions of e.g. multiscale methods and feature based characterisations in the ASTM F3624 standard is expected [37].

The most commonly used parameter for characterising metal AM surfaces is the profile height parameter Ra [38]. This is also the case for manufacturing industry in general [39]. As discussed in publications before, there could be great benefits to adopting more modern and refined approaches to achieve characterisations and specifications that are more functionally relevant and better related to the manufacturing processes [40]. Thus, there is a need for a method to systematically and carefully select an appropriate way to characterise and specify surfaces with complex textures, such as metal AM surfaces.

1.3. Objective and outline of the paper

Given the lack of published scientific information regarding the Hirtisation process, the surface integrity effects and that the process is sometimes suggested as a possible post-process, there is a need for more in-depth information to be made public. Therefore, the main objective of the present study is to evaluate the effect of the post-process on surface integrity properties of an PBF-EB manufactured Ti-6Al-4V component in terms of surface texture and other topographical features. The effect on sub-surface properties is also interesting and will be covered in a future study.

Due to the challenges related to characterisation and specification of surfaces with complex textures, such as metal AM surfaces, a secondary objective is to demonstrate a novel method for combining analyses to facilitate an improved characterisation of surface topographies, that could be especially useful for understanding the effects on surface texture caused by different process steps, such as the Hirtisation process, or some other multi-step processing.

The influence of different processing conditions, such as process settings, process fluid, materials etc, is not investigated in the present study.

In the paper, the case study is described in section 2, including sample preparation in section 2.1 and analysis methods in section 2.2. The results are presented in section 3 with surface texture effects in section 3.1 and other topographical effects in section 3.2. Section 4 contains analysis and discussion regarding the case study results in section 4.1 and regarding the method for combining surface texture analyses in section 4.2. Conclusions are found in section 5.

2. Case study

2.1. Sample preparation

The evaluated samples were manufactured by PBF-EB of Ti-6Al-4V and were post-processed using the Hirtisation process in three steps.

For the PBF-EB manufacturing, an Arcam EBM Q20plus machine was used with a standard 90 μm layer thickness theme for the machine type, version 5.0. The feed stock was gas atomized Ti-6Al-4V powder corresponding to SAE AMS7015 [41]. The parts were further processed by standard HIP (Hot Isostatic Pressure) and annealing heat treatments, corresponding to requirements in SAE AMS4999 [42].

The Hirtisation was performed by Hirtenberger Engineering Surfaces GMBH in a H 6000 S machine. This machine is typically used in prototyping and for serial production purposes. The Hirtisation process is controlled using different exposure times and internal settings for the process such as voltage, current and flow of the medium. The first step, with processing time 2.5 h, had a nominal material removal depth of 500 μm and was for removal of support structures and powder particles. The second and third steps, with processing times 2 h each, both had nominal material removal depths of 200 μm and were for improving the surface finish. Further details regarding process settings and electrolyte used are proprietary and were kept by Hirtenberger.

The four evaluated states were:

1. As printed (AP)
2 After post-processing step 1 (Step 1)
3 After post-processing step 2 (Step 2)
4 After post-processing step 3 (Step 3)

The samples consisted of different areas on the same component that were masked and exposed to the processing steps. The component geometry was a commercial prototype component and details cannot be given. However, the four areas were similar and positioned identically regarding build direction.

2.2. Methods for evaluation

In the present paper, the terms ‘topography’ and ‘texture’ are used to describe the surface shapes. ‘Topography’ is used as a broad term meaning the geometrical shapes and features on the surface in general. ‘Texture’ is what is characterised and quantified using e.g. surface texture parameters defined in ISO 21920-2 or 25178-2.

2.2.1. Surface texture

Surface topographies were measured with a Sensofar S neox instrument using Confocal Fusion [43] with a 20 × objective lens, numerical aperture 0.45. Areas the size of 2188 μm × 1645 μm were measured, by stitching of 3 × 3 areas with 25 % overlap, at 0.645 μm lateral sampling. The Confocal Fusion technique uses a combination of Imaging Confocal Microscopy and Focus Variation [44] and is suitable to use with surfaces containing both smooth areas as well as rougher areas with steep angles [45], such as metal AM surfaces.

The number of measurements needed for representative results was determined in a short separate study by making a large number of measurements (20) in different locations on the AP surface since it had the largest variations. The parameter Sa was calculated since it is the most commonly used areal parameter [39].The 20 measurements were used as a pool of data from which individual measurements were picked randomly and accumulated into mean values with coefficients of variation (CVs) calculated. The CV is defined as the ratio of the standard deviation to the mean. It was repeatedly tested to use an increasing number of measurements to create the mean values and CVs. The change of CV with increasing number of accumulated measurements was used to determine the appropriate number of measurements needed. It was found that using more than 7 measurements did not create more stable CVs. Thus, it was decided that 7 measurements were enough to adequately represent the variation of the surface texture.

Before any analysis was done, the measured datasets were prepared by a spatial median denoising filter, window size 5 × 5 pixels, and form removal using a polynomial of degree 2, creating S-F surfaces. The choice of F-operator (polynomial of degree 2) was because the sample surface geometry was not nominally flat but had a curvature which should be removed. Extreme points were removed by thresholding of the 0.01 % highest and 0.01 % lowest points. After that, non-measured points were filled in using a smooth shape algorithm. All preparation of datasets, filtering, calculation of texture parameters and multiscale analysis was performed using MountainsMap software from Digital Surf. Representative illustrations of topographies, after preparation (S-F surfaces), are presented in Fig. 3 for the four states.

Methods used for evaluation of the surface textures were:

- Conventional texture parameter evaluation
- The multiscale method Area-Scale analysis

For the conventional texture parameter analysis, the calculated selected texture parameters from ISO 25178-2 are presented in Table 1. The selection was based on parameters most used in industry and in related academic literature as well as parameters that would be interesting to explore and compare [38,39]. All analyses were performed on S-F surfaces. For each state, a mean value was calculated together with its standard deviation. The change in mean value from each state to the next was calculated as a difference of means with 95 % confidence intervals. The confidence intervals for the difference of means were calculated using the formula

$$\overline{x}_1 - \overline{x}_2 \pm z\sqrt{\frac{\sigma_1^2}{n_1} + \frac{\sigma_2^2}{n_2}}$$

where $\overline{x}_1$ and $\overline{x}_2$ are the two mean values, z is the coverage factor for a particular confidence level (z = 1.96 in this case for a confidence level of 95 %), σ_1 and σ_2 are the two standard deviations and n_1 and n_2 are the two sample sizes.

Area-scale analysis is based on the idea that the apparent area (*Relative area*) of a rough surface changes with the scale of observation. Relative area is calculated using a tiling algorithm where the topography of the surface measurement is modelled using triangular tiles. At each scale, all tiles have the same area, but not necessarily the same shape. The relative area at each scale is the calculated area at that scale divided by the nominal area. The calculated area at each scale is found by multiplying the number of tiles by the area of the tile at that scale. At large scales, relative area is close to unity. At smaller scales, relative area increase as more surface irregularities can be modelled by the tiling. Thus, going from a larger to a smaller scale, relative area will increase or stay constant until the lateral resolution of the measurement is reached. Complexity is the rate of change in relative area at each scale [2,46].

Characterising a surface texture using relative area is similar to using a lowpass filter with increasingly smaller nesting index and calculating

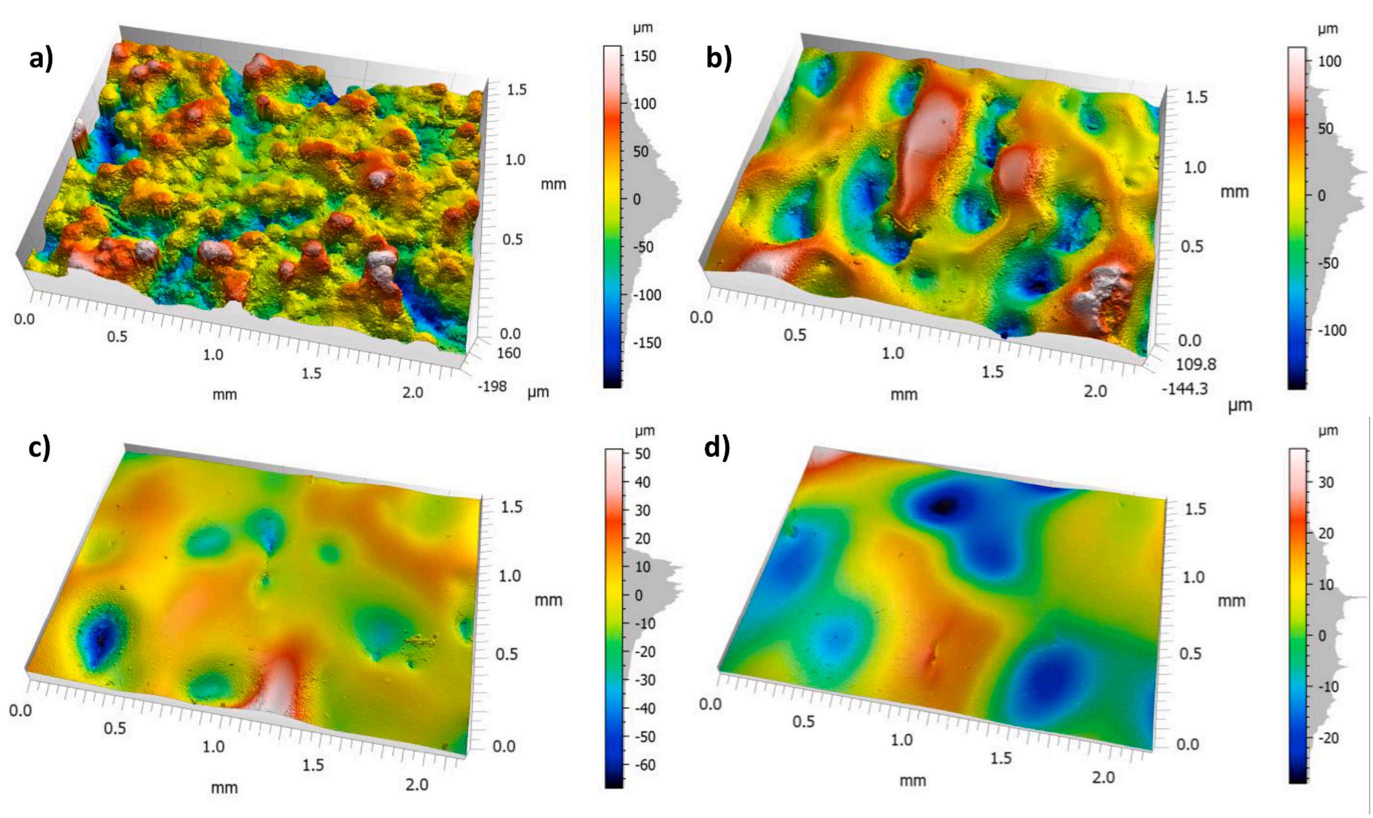

Fig. 3. Representative illustrations of topographies for the four states (S-F surfaces), a) As printed, b) After post-processing step 1, c) After post-processing step 2, d) After post-processing step 3. Note that the colour scales have different ranges. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Mean values and standard deviations for each calculated parameter for the four states.

		Sq	Ssk	Sku	Sa	Sal	Str	Sdq	Sdr	Spd	Spc	S10z	S5p	S5v	Sk	Spk	Svk
AP	**Mean**	50.3	0.0	3.7	38.7	0.1	0.8	3.6	64.5	15.2	8343.8	246.4	128.1	118.3	111.6	52.7	60.0
	St.Dev	7.3	0.3	0.9	5.3	0.0	0.1	0.6	14.0	4.1	7236.8	44.1	19.8	28.6	9.9	9.4	16.1
Step1	**Mean**	41.4	−0.6	4.2	32.3	0.2	0.5	1.6	23.5	4.3	5124.8	166.1	60.9	105.1	90.8	30.2	59.0
	St.Dev	9.7	0.5	1.9	8.9	0.0	0.1	0.4	7.2	2.0	3711.6	23.1	11.2	13.4	27.8	20.0	14.5
Step2	**Mean**	15.3	−0.6	5.0	11.5	0.3	0.7	0.3	2.1	2.7	2689.8	63.6	20.7	40.6	32.1	15.6	22.8
	St.Dev	3.5	0.7	1.6	2.5	0.0	0.1	0.1	0.7	1.5	3548.5	25.5	15.7	12.9	5.1	10.5	5.9
Step3	**Mean**	10.6	−0.3	2.9	8.6	0.3	0.6	0.1	0.7	4.3	10351.9	39.3	16.3	23.0	25.3	8.5	11.3
	St.Dev	2.7	0.4	0.4	2.2	0.0	0.2	0.0	0.2	3.5	16298.8	12.3	5.9	7.7	6.1	5.1	4.1

Sa, or Sq, at each nesting index. It shows how much texture there is at a particular scale, and all larger scales, as an aggregated amount. Complexity is the rate of change in relative area between scales. It is similar to a bandpass filter in the way that it does not include information from larger scales when analysing smaller scales. However, it does not show how much texture there is at a particular scale, like a narrow bandpass filter and calculation of e.g. Sa or Sq would. Instead, it shows at which scales different textures (or features of textures) appear. Thus, changes in complexity values are interesting, not the absolute complexity values in particular, but the scale ranges where the changes occur, because it informs about the emergence of texture that is not present in the other scales.

The parameter Complexity was calculated as function of scale for each measured topography. The parameter Complexity has successfully been used to characterise differences between processing steps in previous studies, e.g. for shot blasting [33] and for hammer peening [47]. The result is a series of x values (evaluated parameter) and y values (scale). A mean value and standard deviation was calculated for every scale from the 7 measurements of each 4 states. The change in Complexity mean value for every scale, from each state to the next, was calculated as a difference of means with a 95 % confidence interval, using the same method as for the conventional parameters analysis.

Conventional texture parameter evaluation and the multiscale method Area-Scale Complexity analysis are used in combination in this study. The hypothesis is that the two types of analyses will give complementary information regarding the surface texture. Conventional parameters informing about significant types of features, e.g. peaks or valleys, or texture properties such as anisotropy, and Area-Scale Complexity analysis providing additional information about the size of the significant features.

2.2.2. Other topographical properties

The near surface microstructure was evaluated on polished cross sections from the as-printed surface and each of the processing steps. Sample preparation was done by cold mounting the samples in epoxy followed by subsequent polishing, finalized by OPS polishing. Investigations of the microstructure was performed in a Jeol 7800 FEG-SEM.

3. Case study results

3.1. Surface texture effects

Mean values and standard deviations from the 7 measurements of each 4 states for all calculated texture parameters are presented in Table 1. The effect of each processing step was calculated as the change in mean value from each state to the next. The results are presented in Table 2 as differences of means with 95 % confidence intervals and the amounts of change, as percentages of the value for the previous state. The cells in rows “Change” are marked green where changes are statistically significant and red where statistically insignificant. The change is significant where a confidence interval does not include 0.

For Complexity, mean values with 95 % confidence intervals for every scale from the 7 measurements of each 4 states are presented in Fig. 4. The change of Complexity from each state to the next, as an effect of the processing step, was calculated as differences of mean values with

Table 2
Effect of each post-processing step, as well as the total effect of all three steps, shown as a mean difference with a 95 % confidence interval together with the amount of change, as a percentage of the value for the previous state, marked in green where statistically significant and red where statistically insignificant.

		Sq	Ssk	Sku	Sa	Sal	Str	Sdq	Sdr	Spd	Spc	S10z	S5p	S5v	Sk	Spk	Svk
Effect of Step1	**Mean diff.**	-8.9	-0.5	0.5	-6.4	0.0	-0.2	-2.0	-41.0	-10.8	-3219.0	-80.3	-67.1	-13.2	-20.8	-22.5	-1.0
	±	9.0	0.4	1.6	7.6	0.0	0.1	0.5	11.6	3.4	6025.1	36.9	16.9	23.4	21.8	16.4	16.0
	Change	-18%	-2107%	13%	-17%	18%	-30%	-57%	-64%	-71%	-39%	-33%	-52%	-11%	-19%	-43%	-2%
Effect of Step2	**Mean diff.**	-26.1	-0.1	0.8	-20.7	0.1	0.2	-1.2	-21.4	-1.6	-2435.0	-102.5	-40.2	-64.5	-58.7	-14.6	-36.2
	±	7.7	0.6	1.8	6.8	0.0	0.1	0.3	5.3	-1.8	3804.1	25.5	14.3	13.8	20.9	16.7	11.6
	Change	-63%	-15%	19%	-64%	63%	36%	-80%	-91%	37%	-48%	-62%	-66%	-61%	-65%	-48%	-61%
Effect of Step3	**Mean diff.**	-4.6	0.4	-2.0	-2.9	0.0	-0.1	-0.2	-1.4	1.5	7662.1	-24.3	-4.4	-17.6	-6.7	-7.1	-11.6
	±	3.3	0.6	1.2	2.5	0.0	0.1	0.1	0.6	2.8	12357.2	21.0	12.4	11.1	5.9	8.6	5.3
	Change	-30%	59%	-40%	-25%	2%	-12%	-53%	-66%	57%	285%	-38%	-21%	-43%	-21%	-46%	-51%
Effect of Steps 1+2+3	**Mean diff.**	-39,6	-0,2	-0,8	-30,1	0,1	-0,1	-3,4	-63,8	-10,9	2008,2	-207,0	-111,7	-95,3	-86,3	-44,2	-48,8
	±	5,7	0,3	0,8	4,2	0,0	0,2	0,4	10,3	4,0	13211,0	33,9	15,3	21,9	8,6	7,9	12,3
	Change	-79%	-935%	-20%	-78%	95%	-16%	-96%	-99%	-72%	24%	-84%	-87%	-81%	-77%	-84%	-81%

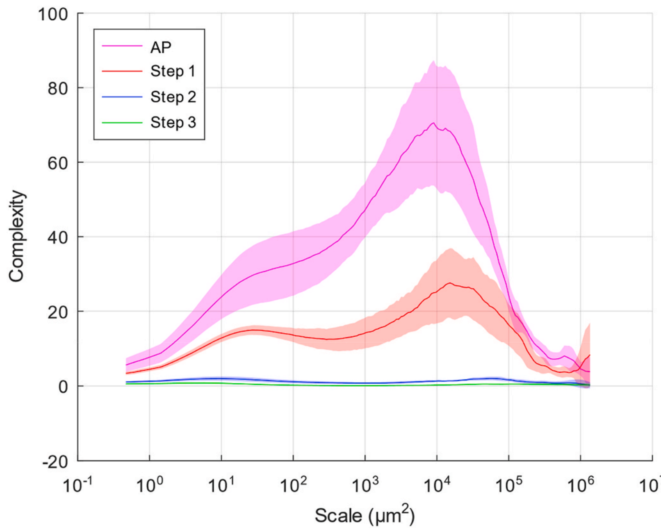

Fig. 4. Complexity values as a function of scale for all states, mean values with 95 % confidence intervals.

95 % confidence intervals. The amount of change, as a percentage of the value of the previous state, for scales with a statistically significant change, is presented Fig. 5. A negative change of Complexity means that the value has been decreased in the analysed processing step.

In Table 2, it can be seen that several parameters are useful for following the changes of the surface texture from one state to the other. The only evaluated parameter that does not have a significant change between any of the states is Spc. All other evaluated parameters have a significant change in at least one of the processing steps. For example, Sdq, Sdr and S10z are reduced in all three processing steps.

Ssk is changed from almost neutral to negative in the first step and then not significantly changed in the two succeeding steps. It seems that the valleys are not so affected in the first processing step, as both S5v and Svk have an insignificant change. However, at the same time both S5p and Spk are significantly reduced by 52 % and 43 % respectively. This corresponds well to the change of Ssk to negative. Str is reduced by 30 % in the first step from 0.8, clearly isotropic, to 0.5, right in the middle of the anisotropic to isotropic range (0 to 1).

The second processing step affects the valleys as well as the peaks. In general, it seems that the second step has the greatest effect since most parameter values, with the exception of Ssk, Sku, Spd, Spc and Spk, are significantly reduced, and Str is increased. The largest significant change is the reduction of Sdr with 91 %.

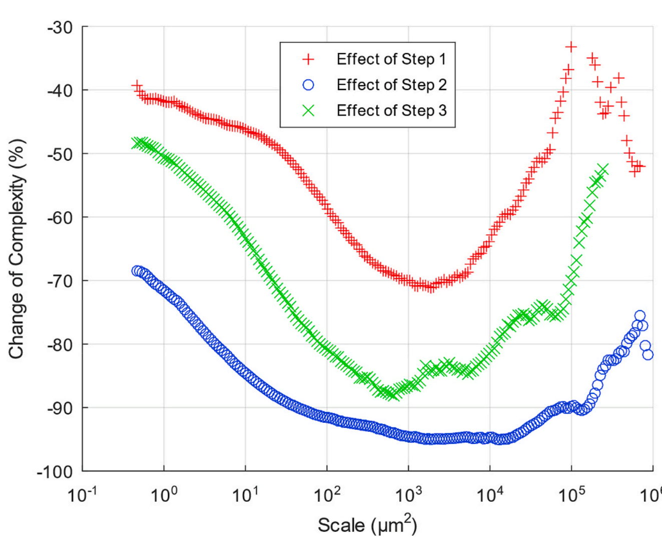

Fig. 5. The relative effect of each processing step, shown as amount of change in Complexity. Calculated as a percentage of the value of the previous state. Only scales with a statistically significant change are plotted.

The third processing step seems to be a general reduction of roughness, including the valleys, but not the peaks, since S5p and Spk, are not significantly reduced. The largest significant change is the reduction of Sdr with 66 %.

In Fig. 5 it can be seen that the processing steps affect the surface Complexity differently. In relative terms, step 1 has a lesser effect on the Complexity and the effect is more markedly focused on scales around 500 μm^2 to 5000 μm^2, corresponding to lengths of about 30 μm–100 μm, since scale is represented by the area of triangular elements in the analysis ($A = 0.5\ L^2$), where the effect is a reduction of Complexity of around 70 %.

Step 2 has the largest effect with a reduction of Complexity of more than 90 % approximately between scales 70 μm^2 to 50000 μm^2, corresponding to lengths of about 10 μm–300 μm, with a maximum reduction of Complexity of about 95 % approximately between scales 1000 μm^2 to 10000 μm^2, corresponding to lengths of about 45 μm–140 μm.

Step 3 has a lesser effect than step 2 but larger than step 1. The maximum effect is almost reaching a 90 % reduction of Complexity, but it is substantially weaker than step 2 for the smaller scales.

3.2. Other topographical effects

The surface microstructures for the as printed and after the different processing steps are presented in Fig. 6. The as printed surface shows some common features of an PBF-EB surface, which contains unmelted powder particles as well as surface pores that create deep and sharp pockets. It is also common that enclosed pores exist in this surface region that are not open to the outer surface. After processing, the surface becomes smoother, and the surface pores are removed successively as the material removal increase. After step 1, after approximately 500 μm material removal, still some deep surface pores are shown which implies that the removal might have been unevenly distributed and transferring the starting surface shapes. The nominal material removal depth is approximately two times the S10z value, the mean hight between the 5 highest peaks and 5 deepest valleys. Thus, all features of the as-printed surface are assumed to have been removed. After step 1, the S10z values is still quite large at just over 166 μm. However, after the following steps, a much smoother surface is produced where no surface pores are observed. These surfaces are generally smooth but show a long wavelength undulation instead.

4. Analysis and discussion

4.1. Effect of post-processing

Analysing and combining the conventional texture parameter evaluation and the Area-Scale analysis, it can be noted that the commonly used height parameters Sa and Sq, areal equivalents to Ra and Rq for profiles, are not significantly changed in the first processing step, see Table 2. However, a large difference can be observed in Fig. 3 comparing a) to b) and in Fig. 5. Thus, there is need for a more refined characterisation of the surfaces to quantify these changes.

For example, the reduction of Complexity in the scales 500 μm^2 to 5000 μm^2 in combination with the reduction of Sdr and S5p could be used to quantify the effect of post-processing step 1. In this case, it seems it would be a measure of the removal of the partially melted powder particles, which are a match in lateral size and are found as broad peaks on the AP surface, but not after step 1. In addition, this interpretation is reinforced by the reduction of Str. The powder particles on the AP surface creates an isotropic texture. When these particles are removed, a more anisotropic surface texture is revealed, with surface texture related to the AM process parameters.

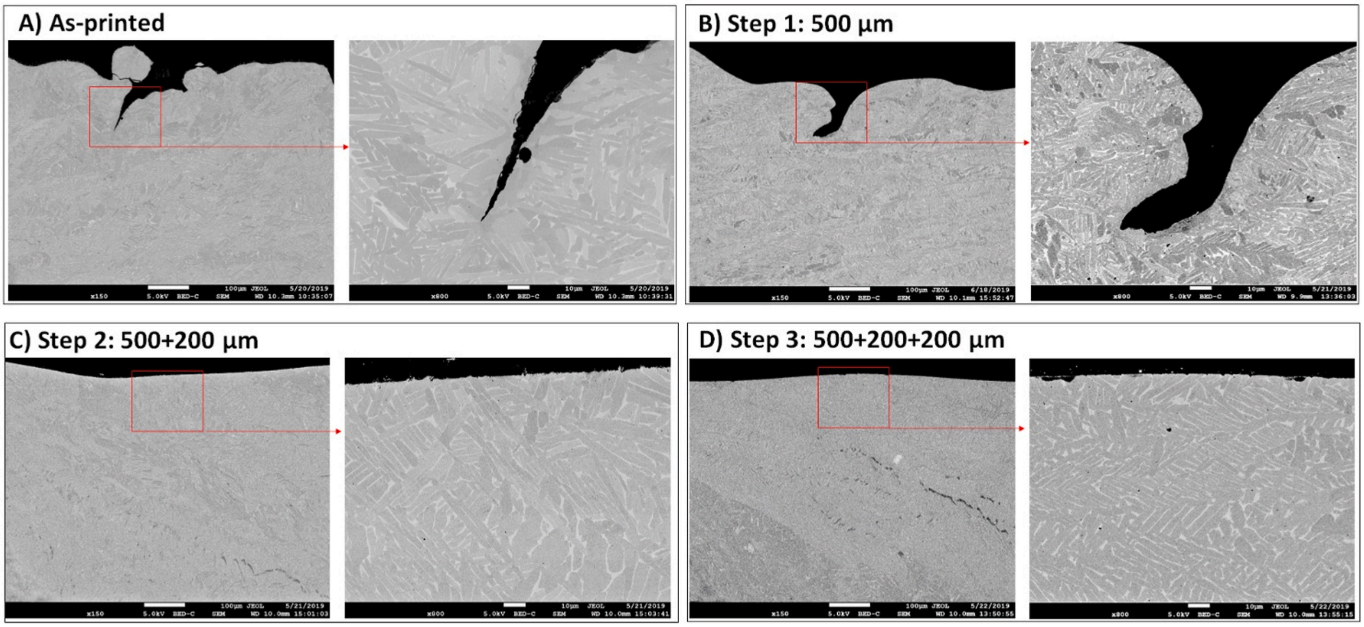

Fig. 6. Representative micrographs of the surface microstructures for A) As printed, B) Step 1, 500 μm material removal, C) Step 2, 500 + 200 μm material removal and D) Step 2, 500 + 200 + 200 μm material removal.

Post-processing step 2 causes such a considerable and general reduction of the surface texture that many parameters could be used to characterise the effect. E.g. the reduction of Complexity in the scales 70 μm^2 to 50000 μm^2 in combination with the reduction of Sdr and increase in Str, with the anisotropic features, the AM process signature, seen after step 1 reduced. In summary, the surface texture becomes significantly smoother and isotropic.

Post-processing step 3 is slightly more difficult to characterise as the reduction of roughness is smaller in absolute terms and seems to be affecting the valleys more than the peaks. Here, a combination of the reduction of Complexity in the scales 100 μm^2 to 10000 μm^2 and the reduction of Sdr and S5v could be used.

Analysing the total effect of the three processing steps, see Table 2, it is evident that the post-process has drastically changed the surface texture. E.g. averaging height parameters such as Sa and Sq have been reduced by 78 % and 79 % respectively, which is in-line with previously reported results [18,21,22]. The absolute values are difficult to compare directly between studies since the surface texture characterisation has been performed differently.

However, the largest change can be seen in Sdr and Sdq, which have been reduced by 99 % and 97 % respectively. Sdr is a measure of how much surface area that is available in relation to the nominal area, similar to relative area, but Sdr is only calculated at the sampling scale. Sdq is a measure of the average slope of the surface in each point. Both these parameters are more sensitive to small scale texture in comparison to Sa and Sq.

In addition, examining the parameters focusing on peak and valley regions, such as S10z, S5p and S5v, it can be seen that both peak and valley regions have been greatly affected. The highest peaks, S5p, have been reduced by 87 % and the deepest pits have been reduced by 81 %.

Klingvall Ek reported that the fatigue properties of PBF-EB manufactured Ti-6Al-4V samples were significantly improved by Hirtisation post-processing because of the reduced surface roughness, quantified as Ra [24]. In the present study, it is shown that not only is the average roughness reduced by the post-process, but there is an even greater change regarding less deep pits and less steep slopes on the surface, which explains the positive fatigue results further.

Measurement of rough as-printed surfaces is challenging since the instrument needs to handle difficult to measure features such as sharp and narrow channels or pores, and surfaces hidden by unmelted powder particles, as shown by the cross sections, because such features give limited access to the real surface shapes [38,48]. Thus, care must be taken when drawing conclusions regarding the real surface topography based solely on surface topography measurements on very complex surfaces. In the case of the present study, this pertains to the as printed state.

4.2. Methodology for surface texture evaluation

With the conventional parameters it is possible to follow the changes between the processing steps and also get an idea of what type of features that are being affected, e.g. peaks or valleys. However, it is not possible to analyse the size of the affected features, which is possible with a multiscale method such as Area-Scale analysis.

The disadvantage of only using a multiscale method, as Area-Scale Complexity analysis, is that it is insensitive to many things that the conventional parameters quantify, such as anisotropy or if the texture consists of peaks or valleys. These are good motives for using a combination of the techniques to achieve a more detailed and complete surface texture characterisation.

The novel method demonstrated in the present paper, using statistics and tools such as Table 2 and Fig. 5, can be an efficient and systematic approach for selecting relevant parameters for evaluation and aid the interpretation of the observed phenomena. Also, since the conventional surface texture parameters each quantify only one aspect of the texture, it is useful to use more than one to achieve a more complete description of the texture. However, care should be taken to choose parameters that quantify different, and complementary, aspects.

Another method that could be used for selecting parameters that combine conventional parameters and multiscale analysis is described by Krishna et al. [33]. There, the multiscale analysis is used to define filters and the correlation between conventional parameter values and the multiscale parameter is used for selecting suitable conventional parameters to evaluate for the filtered scale ranges.

5. Conclusions

The evaluated post-process Hirtisation greatly changed the topography of the workpiece. E.g. Sdq was reduced by 97 %, S5v was reduced by 81 % and Sa was reduced by 78 %, comparing as printed to after processing step 3. A surface texture with much lower average roughness, less deep pits and less steep slopes has been produced, which is expected to be beneficial for improved fatigue properties.

The three process steps had different effects on the surface topography regarding the types and sizes of features that are affected. Using only Sa, as is very common, was not sufficient to characterise the different effects. The conventional parameter evaluation gives a basic, but not complete, understanding of how the texture is affected by the processing steps. It informs about significant types of features, e.g. peaks or valleys, or texture properties such as anisotropy, where changes occur. However, it does not inform about the size of these significant features.

A multiscale method, such as Area-Scale Complexity, is very complementary to conventional parameter evaluation since it gives information about the size of features of interest. However, used on its own it has disadvantages. E.g. it is insensitive to several things that the conventional parameters quantify, such as anisotropy or if the texture consists of peaks or valleys.

The novel method demonstrated in the present paper is a combination of the techniques conventional parameter evaluation and Area-Scale Complexity that can be used to efficiently achieve a more detailed and complete surface texture characterisation, and aid the interpretation of the observed phenomena.

The case used in the paper is regarding subsequent processing steps, but the method could just as well be used to compare different process settings for one process or for selecting parameters and suitable values for tolerancing.

CRediT authorship contribution statement

J.B.: Conceptualization; Formal analysis, Investigation, Methodology, Writing - original draft, Writing - review & editing. J.H.: Investigation, Writing - original draft, Writing - review & editing. K.W.: Writing - review & editing. R.S.: Writing - review & editing.

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Data availability

Data will be made available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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