euspen's 22nd International Conference & Exhibition, Geneva, CH, May/June 2022
www.euspen.eu

Areal topography evaluation of a Ni-based alloy printed by electron beam melting (EBM) process

R. Tomkowski[1], X. Zhao[1], A. Leiro[2], A. Archenti[1]

[1]Production Engineering Department, KTH Royal Institute of Technology, Brinellvägen 68, Stockholm 11428, Sweden
[2] Materials Technology YTMN, Scania CV AB, Granparksvägen 10, 151 87 Södertälje, Sweden

rtom@kth.se

Abstract
Electron beam melting (EBM) is a powder bed fusion (PBF) additive manufacturing (AM) process for metal powder printing with wide applications in key industrial sectors, including automotive, healthcare, aerospace, etc. The high-temperature processing of this technique extensively sinters the powders on the surfaces and creates a poor and coarse surface finish. Differences between the surfaces from EBM in comparison with other AM processes make it difficult to answer which measurement method, with what measurement settings, and which evaluation parameters should be used for surface characterization. In this work, the performance of various optical methods for the measurement of areal topography of rough EBM-made metal surfaces was investigated. A specially prepared artefact allowing for the generation of different angles was designed and produced from a nickel-based alloy using EBM without any supporting structure for down-facing surfaces. The as-built up-facing and down-facing surfaces from the artefacts were measured in orthogonal to the build direction. Measurement system capability for as-EBM surfaces is presented along with areal surface texture analysis.

Keywords: electron-beam melting, measurement, surface texture, areal topography

1. Introduction

Additive Manufacturing (AM) is considered a future manufacturing system, where complex external and internal structures can be manufactured. The technology allows printing layer-by-layer components of a great degree of complexity, which is not possible to do by using traditional (subtractive) methods. Moreover, a broad spectrum of materials can be used to manufacture parts, from polymers to metals.

The most popular technique to print metallic components is Powder Bed Fusion (PBF). The PBF processes use a high energy source (laser or electron beam) to selectively melt the material based on the sliced model to create desired solid structure (element). One of the biggest challenges of the PBF processes is the final surface quality of the part, which also varies among different PBF methods (selective laser melting (SLM), Electron beam melting (EBM), etc.). This limitation has a great impact on the quality control of AM manufactured parts. So far, non of the PBF method, or AM part in general, can produce surfaces "ready to use". Rather, they are "as printed", as Reese et. al [1], proposed the term, and they are ready for further treatment. It is possible to monitor the surface to improve and optimize the printing process whereby by lowering surface roughness, the machining allowance can be kept at the minimum level.

The surface quality of AM parts is of great interest to many researchers worldwide. Thompson et. al [2], analyzed internal surfaces of the metal PBF part by using various measurement techniques, with the main focus on XCT, as was extensively done also by Townsend et. al [3]. The qualitative comparison of areal parameters was made, concluding beneficial of using XCT for areal topography assessment. There is still a lot of work to be done in it, e.g., to secure accuracy and repeatability, but results are very promising.

Lou et. al [4], were focusing on different characterization methods of surface topography for PBF surfaces. The waviness is equally important as roughness, for AM parts. Therefore a careful selection of filtering techniques and filtering parameters, such as cut-off (nesting-index), are important factors in the quantification of the surface texture. It was concluded that robust Gaussian regression filter and morphological filter are qualified for PBF surface analysis. Also, it was pointed out that AM manufactured surfaces contain other spatial surface features, like globules and surface pores, which cannot be neglected, as can help improve the printing process. Netwon et al. [5], were characterizing EBM surfaces with a particular focus on surface features. The combination of feature-based analysis with conventional characterization (called by authors "hybrid characterization") can provide new information, e.g., for planning the surface finishing process.

Zhu et. al [6] were looking for a correlation between areal surface texture parameters with processing parameters and component porosity after High-Speed Sintering (HSS). They use Focus Variation (FV) method for surface data acquisition. It was concluded that the amplitude parameter correlates strongly with porosity level, well supported by examples of EBM and SLM surfaces analysis. Newton et. al [7] also performed areal topography measurements of metal AM surfaces using FV. The main focus was on the FV microscope's capability of obtaining reliable surface measurements. Measurements were done only on flat surfaces, but it showed that the amplitude parameter *Sa* wasn't much affected by different measurement parameters. Sidambe [8] analysed a three-dimensional surface topography, using white light interferometry. He analyzed three different surface roughnesses with orienting the builds in three angles 0°, 55°, and 90°, in the EBM build chamber. The study showed that EBM can be used to fabricate specific surface textures, but more importantly, it was concluded that inclining the component can lead to a rougher surface.

This study has been carried out because there is a need for printing process optimisation. The main focus of this study was capturing optical methods capable of measuring as-EBM surfaces. This can be achieved by the ratio of non-measured points analysis, followed by a deeper study of areal surface texture parameters. Both approaches are presented in this paper.

2. Methodology

2.1. Printing strategy

In this work, the gas atomized IN625 powder (Osprey® Alloy 625 from Sandvik, Sweden) was used to produce the samples. The powder was recycled having a spherical shape with some non-spherical residuals. These are small particles resulting from the printing and recycling process. The average size of the powder particles is 75 µm where 95% of the powder was between 45 and 105 µm.

Two types of samples had been produced using an Arcam (a GE Additive, Sweden) A2X EBM machine at 1025˚C. One was printed with only a hatching strategy while the other one was printed using an extra high energy continuous contour (HECC) after hatching. The detailed processing parameters can be seen in the work of Zhao et. al [9].

The design of the samples could be seen in Figure 1. These artefacts consist of 7 cubes with a side length of 10 mm, with different orientations to the starting plate. The front surface of the cubes is marked with the corresponding rotation angle. While the top (Figure 1a red marks) and bottom (Figure 1b blue marks) surfaces are the targeting ones for the surface analysis. The samples were directly built on top of the start plate to prevent thermal distortion and minimize the influences from support structures to the downfacing surfaces. Therefore, the bottom surfaces of 0° and 15° parts had been sacrificed. Accordingly, the cubes with 0° and 15° had been printed separately with minimum supporting structures, as shown in Figure 2. Thus, in total 2 artefacts and 4 separate samples were printed.

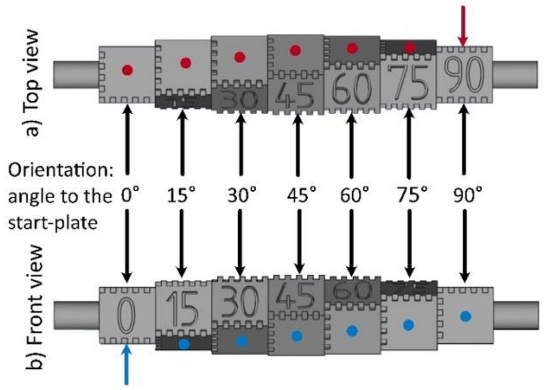

Figure 1. The design of the artefact with a) top view and b) front view. The red dots and arrows in a) demonstrate the up-facing surfaces while the blue ones in b) indicate the downfacing surfaces.

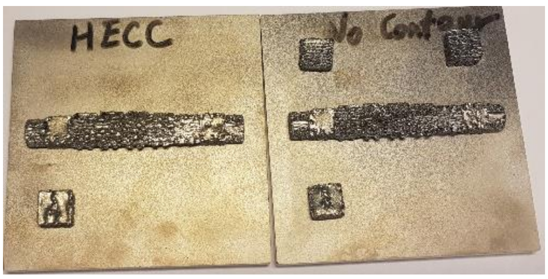

Figure 2. As-printed components.

The supporting structures of the extra 0° and 15° samples were located at the border and centerline of the testing samples, as highlighted in Figure 3. The measurements will be performed out of these regions. In addition, the top surfaces of these samples would be skipped. The ones on the artefacts having the same orientation were used for top surface analysis. The targeting surfaces on the as-printed parts are shown in Figure 4. The actual top and bottom surfaces were marked with black white colours, respectively.

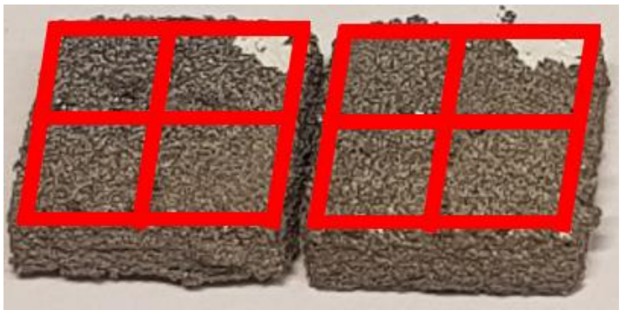

Figure 3 The demonstration of the location of supporting structures as highlighted in the red zones.

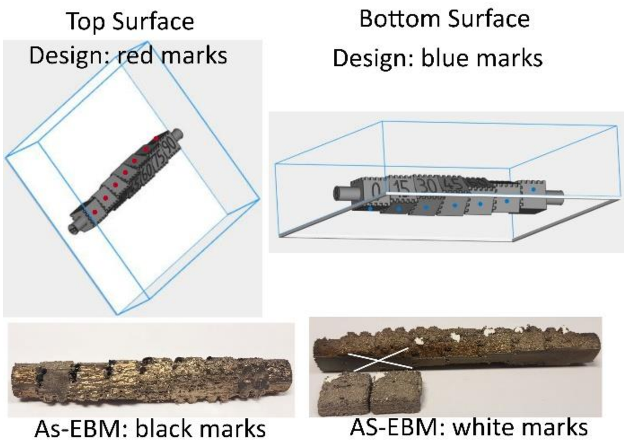

Figure 4. As-printed components.

2.2. Measurement strategy

Optical profiler Seonsofar S NEOX 6 was used to perform the measurement. Two lenses with 50x magnification were used for surface texture data acquisition, first for Coherent Scanning Interferometry (CSI) and second for Confocal Scanning Microscopy (CSM) and Confocal Fusion (combination of CSM and Focus Variation - FV). The parameters are presented in Table 1.

Measurements were done with the use of three different methods (CSI, CSM, and CF) of the same measurement area, only by changing objective and/or control software settings.

No stitching method was used in the measurement process. This was due to eliminating a lateral movement error replication, together with possible software-induced stitching error, from the measurement.

Table 1 *Objectives parameters on Sensofar S NEox 6 optical profilometer*

	Brigthfield	Interferometry
Magnification	50x	50x
NA	0.8	0.55
Working distance (µm)	1.0	3.4
Field of view (µm)	340x284	340x284
Optical resolution (µm)	0.17	0.28
	Confocal	**CSI**
Verical resolution (µm)	3	1 nm
Maximum slope (°)	42	25
	Focus Variation	-
Min measurable roughness	Sa > 10 nm	
Maximum slope (°)	Up to 86°	

2.3. Data processing

The analysis was divided into two steps. In the first step, the ratio of non-measured points was analyzed, as an indication of measurement method capability. In the second step, surface texture parameters were calculated and analysed, for each printing strategy and each printing building angle.

The Robust Gaussian Regression Filter (RGRF) was chosen to perform bandwidth filtering, as this filter included compensation of filtered profile distortion at the end of the profile, in comparison to standard Gaussian filtering. All surfaces were under the following processing:

- Levelling, least-squares form-fitting using an LS-plane, by subtraction,
- Filtering with RGRF according to ISO 16610-31 [10],
- Waviness (S-F surface) and Roughness (S-L surface) areal surface texture analyses according to ISO 25178 [11].

All measured surfaces were analyzed in the surface metrology software MountainsMap Imaging Topography 7.4.9391. Statistical analysis was calculated in Matlab R2021a.

3. Results and Discussion

3.1. Measurement technique capability assessment

Usually, the first measurement of the surface is a blind trial. The surface feature characteristics, like those after the EBM, determine, to a great extent, the outcome of the optical measurement. All three tested methods have limitations that originated from their physic. The main limitation, or difference between all methods, is the ability to measure surfaces with different wall build angles.

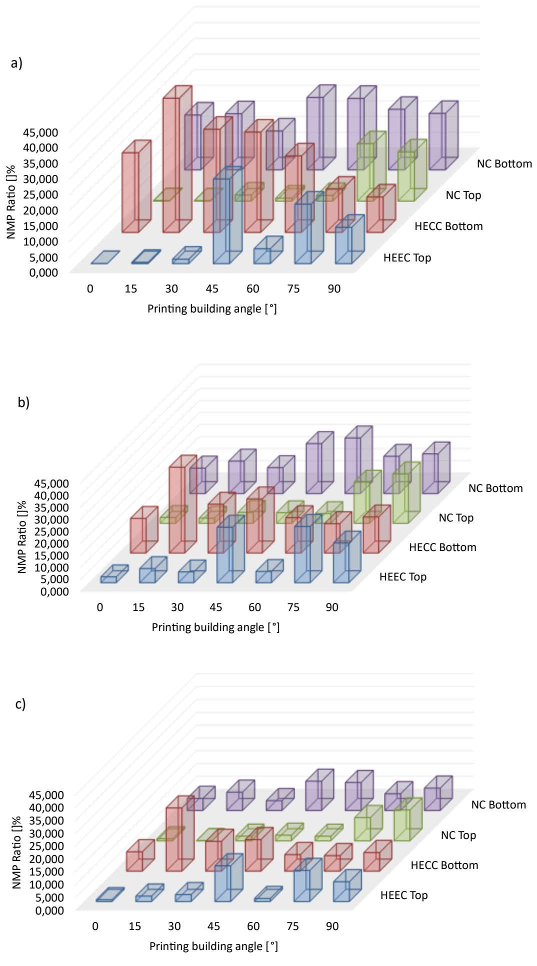

Figure 5. Non-measured points ratio (NMP) assessment for different optical measurement methods: (a) CSI, (b) CSM, (c) CF

Taking that into account, one can expect that number of non-measured points ratio can be a good indicator of the measurement method capable of measuring EBM surfaces. Figure 5 shows 3 images of the NMP ratio for two different artefacts which were measured on the top and bottom surface with three different optical methods. It can be seen that the lowest ratio is for confocal fusion. This can be explained by the fact that the focus variation method (a part of confocal fusion) allows measuring surfaces with a wall elevation angle up to 86°.

This analysis reveals also, that bottom surfaces are more difficult to measure to their higher porosity. Nevertheless, by comparing measurement methods, one can observe that the NMP ratio is similar to each building angle, but it looks like it is scaled down (going from CSI to CF). This also strongly depends on the area of the surface chosen to be measured and the ratio can change a bit indifferent measuring point.

3.2. Areal topography evaluation

Usually, and traditionally, surface texture analysis is directly connected and designed to monitor manufacturing processes. AM surfaces are not typical surfaces. Moreover, they are not for direct use. Rather, they require separate, after printing treatment (e.g., subtractive machining) to comply with GPS requirements and provide desired surface functionality. Knowing this, it can be assumed that AM metal surface analysis can provide necessary information to optimize the printing process.

Cut-off selection

The selection of the correct cut-off for bandwidth filtering of EBM surfaces is not an easy task. There are plenty of factors that need to be taken into consideration while choosing filtering parameters. However, the proper cut-off selection mostly depends on (among others) surface complexity, function, and measured area (Figure 6).

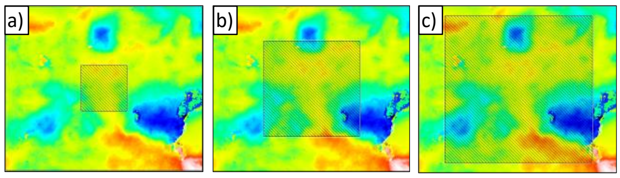

Figure 6. different cut-off size of over the surface area (338 µm x 284 µm): (a) 80 µm, (b) 165 µm, (c) 250 µm, contributing to filtering and separation of roughness and waviness.

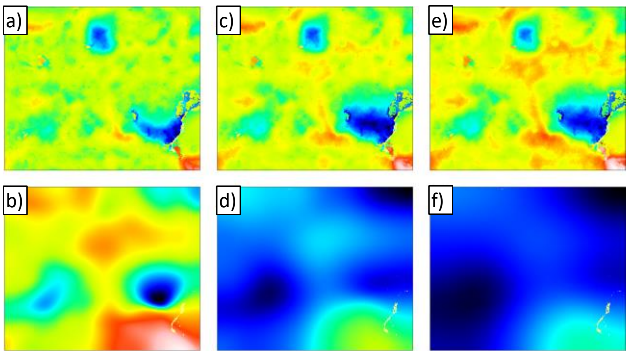

Figure 7. Roughness and waviness after using RGRF with three different cut-offs: (a, b) 80 µm, (c, d) 165 µm (e, f) 250 µm.

As presented in Figure 7, using RGRF with different cut-offs reveals, that a small cut-off does not make a proper separation of waviness and roughness. However, more study is needed for a more objective cut-off selection. In this paper, it was decided that cut-off = 250 µm is giving the most satisfactory separation. This is because the EBM surfaces contain a lot of features, like globules, high peaks, and pores, which are rather part of roughness than waviness.

Selected areal texture analysis

Several areal texture parameters were calculated and analyzed. All parameters were calculated for the NC TOP, NC BOTTOM, HECC TOP, and HECC BOTTOM surfaces, at 0 to 90 deg at every 15 deg. In total 28 surfaces were measured with three different methods, giving 84 different measurements.

In this study, only two parameters will be presented for roughness surfaces, *Ssk* surface skewness and *Sku* surface kurtosis. *Ssk* defines the distribution of height values above or below the mean plane. The surface has sharp peaks for positive *Ssk* values and is blunter for negative *Ssk* values. *Sku* defines the geometry of the peaks and valleys. Surfaces with *Sku* higher than 3 for the height distribution are considered sharp, while *Sku* lower than 3 are considered even. Both parameters relate to the hights values distribution.

Most of the calculated *Ssk* values remain negative for down-skin (bottom) surfaces, while for the up-skin (top) surfaces *Ssk* values are mixed (negative and positive), as presented in Figure 9. (a, c, e). Negative values of *Ssk indicate* pores and non-sharp peaks on the surface, as the distribution of the surface z-values deviates towards the upper side. Surfaces, which contain sharper peaks or other features pointing from the surface have positive *Ssk* values. Positive *Ssk* values were found for NC TOP surfaces at 15 deg, 30 deg, and 60 deg, independently of the used measurement method.

Sku analysis shows that for all surfaces textures are considerably sharp, as their values exceed number 3. This is especially visible at 75 deg for the HECC BOTTOM surface.

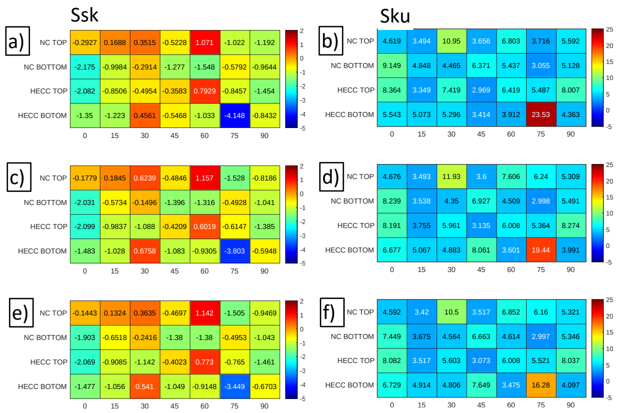

Figure 8. Heatmap representation of skewness (*Ssk*) and kurtosis (*Sku*) for three optical measurement methods: (a, b) CSI, (c, d) CSM, (e, f) CF. The X-axis represent the build angle in deg, Y-axis represents surfaces after different printing strategies (non-contouring and contouring).

4. Conclusion

This study investigated different build inclination angles of the EBM up-skin and down-skin surfaces, for two different printing strategies (with and without contouring). Surfaces were measured with three different optical methods. Several areal texture parameters were calculated along with a non-measured points ratio. The selection of cut-off for RGRF was analysed. Based on the study following conclusions can be drawn:

- the cut-off selection is an important task. Authors recommend analysing roughness and waviness simultaneously, as it can give a complementary view of the surface. Moreover, can indicate which printing parameters can be improved.
- non-measured points analysis shows that confocal fusion (CF) is the most capable optical method for measuring EBM surfaces, giving the lowest NMP ratio in the Z direction. However, surface parameters from CF measurements have higher values and spread than surfaces measured by the CSI method.
- surface texture parameters analysis indicates that the NC surfaces are denser and smoother than HEEC surfaces. This is can be attributed to the lower local temperature of slices during printing. These were resultant of two aspects: i) the energy input for HECC is 7.5 times higher than the hatching region, ii) the cubes were sitting next to each other imposes extra heat from neighbour ones.
- surfaces at 0 and 90 deg are the smoothest ones in comparison to other build angles. Also, in general, down-skin surfaces are much rougher than up-skin surfaces, but parameters vary.

The surface quality control has a monitoring meaning, for the EBM process. It means, that there is room for printing optimisation in terms of surface quality improvement. Lower surface height can significantly reduce the allowance for machining, or other surfaces finish after printing.

References

[1] Z. C. Reese, J. S. Taylor, and C. J. Evans, Surface finish metrology of additive-manufactured components, in *Proceedings - ASPE/euspen 2016 Summer Topical Meeting: Dimensional Accuracy and Surface Finish in Additive Manufacturing*, 2016, pp. 50–54.

[2] A. Thompson, N. Senin, I. Maskery, L. Körner, S. Lawes, and R. Leach, “Internal surface measurement of metal powder bed fusion parts,” *Addit. Manuf.*, vol. 20, pp. 126–133, Mar. 2018, doi: 10.1016/j.addma.2018.01.003.

[3] A. Townsend, N. Senin, L. Blunt, R. K. Leach, and J. S. Taylor, “Surface texture metrology for metal additive manufacturing: a review,” *Precis. Eng.*, vol. 46, pp. 34–47, Oktober 2016, doi: 10.1016/j.precisioneng.2016.06.001.

[4] S. Lou, X. Jiang, W. Sun, W. Zeng, L. Pagani, and P. J. Scott, “Characterisation methods for powder bed fusion processed surface topography,” *Precis. Eng.*, vol. 57, pp. 1–15, Maj 2019, doi: 10.1016/j.precisioneng.2018.09.007.

[5] L. Newton, N. Senin, E. Chatzivagiannis, B. Smith, and R. Leach, “Feature-based characterisation of Ti6Al4V electron beam powder bed fusion surfaces fabricated at different surface orientations,” *Addit. Manuf.*, vol. 35, p. 101273, Oct. 2020, doi: 10.1016/j.addma.2020.101273.

[6] Z. Zhu, S. Lou, and C. Majewski, “Characterisation and correlation of areal surface texture with processing parameters and porosity of High Speed Sintered parts,” *Addit. Manuf.*, vol. 36, p. 101402, Dec. 2020, doi: 10.1016/j.addma.2020.101402.

[7] L. Newton *et al.*, “Areal topography measurement of metal additive surfaces using focus variation microscopy,” *Addit. Manuf.*, vol. 25, pp. 365–389, Jan. 2019, doi: 10.1016/j.addma.2018.11.013.

[8] A. T. Sidambe, “Three dimensional surface topography characterization of the electron beam melted Ti6Al4V,” *Met. Powder Rep.*, vol. 72, no. 3, pp. 200–205, May 2017, doi: 10.1016/j.mprp.2017.02.003.

[9] X. Zhao, S. Dadbakhsh, and A. Rashid, “Contouring strategies to improve the tensile properties and quality of EBM printed Inconel 625 parts,” *J. Manuf. Process.*, vol. 62, pp. 418–429, Feb. 2021, doi: 10.1016/j.jmapro.2020.12.007.

[10] ISO 16610-31:2016 Geometrical product specifications (GPS) — Filtration — Part 31: Robust profile filters: Gaussian regression filters. International Standards Organization: Geneva, Switzerland.

[11] ISO 25178-2, 2012, Geometrical Product Specifications (GPS)— Surface Texture: Areal—Part 2: Terms, Definitions and Surface Texture Parameters. International Standards Organization: Geneva, Switzerland.