Topographical evaluation of laser generated surfaces using statistical analysis of surface-normal vector distributions

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Abstract. Surfaces generated by Additive Manufacturing or laser texturing can involve the solidification of droplets of liquid, which can give rise to overhanging features on the solidified surface. Overhanging features add a layer of complexity to the surface topography and are undetectable by standard surface roughness measurement techniques such as profilometry. Such features are important because they can have a considerable effect on surface properties such as wettability. New techniques and algorithms are therefore required to analyse and quantify convoluted surfaces with overhanging (re-entrant) features. Earlier work by the authors introduced the concept of using X-ray micro-computed tomography (Micro-CT) to identify the directions of vectors normal to the surface at any point and thus indicate the presence or absence of overhanging features. This paper divides overhanging features into two types; simple and compound, and introduces new, size independent, analysis techniques which measure what proportion of each type is on the surface. Another extension of the analysis is the comparison of surface profiles taken in different directions in order to identify any surface roughness anisotropies.

1. Introduction
Additive manufacturing (AM) [1], laser surface texturing [2–4] and thermal spray coating, often involve the attachment of droplets to a solid substrate. These techniques can generate new types of technical surface which, as Godi et al. have pointed out, often cannot be characterised according to the current ISO standards [5]. For example, some AM surfaces include overhanging features (also referred to as re-entrant features) like those described in figure 1. Overhanging features of this sort cannot be measured by mechanical or optical surface roughness measuring tools.

One example of the useful application of overhanging features on technical surfaces is the field of medical implants.[6] The classification of implant surface structures is a field where e.g. Wennerberg and Albrektsson[7] have pointed out the need for a more uniform terminology and have created a set of guidelines for topographic evaluation of surface defining parameters such as form, waviness and roughness. Compared to a smooth metal surface, a nanoscale oxidized surface layer improves the deposition of the bone matrix hydroxylapatite, the adsorption of proteins, the adhesion of cells, and the overall rate of osseointegration. [8][9] Integration can be improved and accelerated even further if this type of surface is produced on a micro-rough surface involving overhangs. This is because the overhangs provide areas for excellent mechanical locking [10], which is reinforced by apatite formation in the surface irregularities.[11] Laser pulses can be used to create “splashy” surfaces involving suitable overhanging features[12,13] including attached droplets of 1-5 µm diameter.[6,14,15] These types of laser-treated surfaces provide a better topography for cell growth[16] than those produced by acid-etching or sandblasting.[17] Laser texturing can also optimise surface energy, which improves protein adsorption and cell attachment.[18] Wennerberg et. al. [19] in their study of bone response to different surface roughness, also pointed out the limitations of Rₐ and Sₐ, as measures when comparing different textures.

X-ray computed tomography (X-ray CT) can be used for stress analysis of Additive Manufacturing (AM) surfaces which are covered with attached droplets.[20] In this work Kantzos et al. identified overhanging features and surface porosity. A thorough discussion about the classification of complex surfaces (periodic, non-periodic, etc.) can be found in “A Taxonomy for Texture Description and Identification” by Rao[21]. An investigation about how traditional roughness metrics (Rₐ, Rₛ etc.) for surfaces generated by AM are affected by factors like laser power, slice size, scanning speed etc. has been carried out by Calignano [22]. Senin et al.[23] highlight the difficulties of reliably quantifying the
topography of AM generated surfaces and comment that results can even be ‘heavily dependent on instrument make and model’. Pagani et al. presented in 2017 [24] a powerful technique for defining surface texture parameters for free-form surfaces using a triangular mesh with parametrization of the surfaces and B-spline reconstruction using the software platform SurfStand. The dominant factors were identified using Principal Component Analysis (PCA). Their ideas were developed further in [25] which describes complex freeform surfaces (also involving normal vectors) as a tool for classifying complex overhangs. (In their paper complex overhangs are named “re-entrant features”). Newton et al. [26] have presented developments in the field of feature-based surface characterisation which are particularly suited to AM generated surfaces.

Earlier work by the present authors [3,27-28] introduced a new approach for the characterization of complex surfaces which enables a quantitative description of overhanging features. The technique uses computed micro-tomography to map the surface. From the tomography data cross sectional traces are generated, which include all the overhanging features (see figure 2).

Figure 1. For surface profiles, overhanging features are invisible to traditional roughness measuring devices, such as (a) mechanical stylus profiling or (b) White Light Interferometry (WLI), measured here by a Wyko instrument.

These cross-sectional surface traces can have equally spaced surface-normal vectors allocated to them as shown in figure 3 (and for a simplified, artificial surface in figure 4). Statistical tools can then be employed to analyse the variation in surface-normal vector inclination for different types of surfaces. Zhang et al have investigated the usefulness of histogram representations of surface features [29] and Tang et al have explored the use of normal surface vector histograms as a method of surface classification [30]. The work involved recognition of objects and object classification in computer vision applications using information from a depth sensor. Similar techniques, using information from histograms of normal vectors for object classification in computer vision applications have been used by e.g. Watanabe [31] and Dalal [32]. However, this approach has not been used for the classification of engineering surfaces.

Figure 2. (a) Typical micro-tomography view of a rough surface created by additive manufacturing - note overhanging features, (b) a cross section taken from the tomography data.

Figure 3. Surface profiles with equi-spaced surface-normal vectors: (a) surface normal vectors for mechanically roughened surfaces would have an inclination range of less than 180 degrees; (b) overhanging features introduce a much wider range of surface normal vectors.
For technical surfaces created by the accumulation of droplets, the distribution of the angles of surface-normal vectors can give quantitative and qualitative information about the presence or absence of overhanging features. This paper builds on the earlier work and presents, for the first time, analytical techniques for identifying two types of overhangs: simple and compound. Both types of overhangs can have a negative effect on wettability, but compound overhangs have a greater ability to trap air and thereby prevent local wetting. This work also presents a statistical tool which can be used for identifying cyclic patterns within the roughness of convoluted surfaces.

2. Methodology

Four different types of surfaces were created for this investigation. Titanium samples were prepared as follows:

- A grit blasted surface; grit blasted with Zirconium dioxide, Cerablast K125 (0-125) µm.
- A Laser BioHelix™ surface; a proprietary technique used for structuring the surface of medical implants.
- An Additive Manufactured (AM) surface; produced by additive manufacturing using 45-150 µm powder.
- An etched AM surface; The raw AM surface (as above) subsequently etched with a zinc chloride solution comprising ethyl alcohol (700 ml/l), isopropyl alcohol (300 ml/L), aluminum chloride (60 g/l), and zinc chloride (250 g/l) as described by [33].

The AM-samples were manufactured in an ARCAM-A2 EBM machine using standard firmware and with a 50 µm layer thickness. The powder material was Ti6Al4V- Grade 5 with the particle distribution 45-150 µm supplied by Arcam EBM. Standard Arcam-A2 MultiBeam™ technology was used with two contours. The beam settings for the outer contour were: 340 mm/s and 4 mA, 40 spots, and for the inner contour 80 mm/s, 10 mA and 15 spots.

The BioHelix surface is a proprietary laser treated implant surface patented by Integrum AB, Gothenburg, Sweden. It is generated by exposing a Titanium surface to an intense bombardment of Nd:YAG Q-pulses of roughly 200 ns length and 1.3 W average power. (See Olsson [27,28]). All four samples were analysed with a Micro-CT instrument (Zeiss XRADIA 510 Versa) with a resolution of 0.5 µm in the X, Y and Z directions. Slices from the Micro-CT 3D topographies of the samples were analysed in a MATLAB-code using the steps described in Table 1, which are illustrated (for a simplified artificial topography) in figure 4 (a). This analysis produced histograms of the distribution of the surface-normal vectors for each cross-section.

**Figure 4.** Example surface profile for the workflow: (a) surface profile with six different domains numbered (1)-(6), (b) calculation of equidistant surface vectors, (c) normal vector angle as a function of the curve position along the profile, (d) histogram of normal vector angles.
Table 1. The workflow applied in generating the surface-normal vector histograms.

| Step | Task |
|------|------|
| a.   | Roughly isolate the region of interest (ROI) from a Micro-CT image. |
| b.   | Isolate the ROI in detail. |
| c.   | Generate contour. |
| d.   | At evenly spaced distances calculate normal vectors and normalize them to unit length. |
| e.   | Calculate and plot the results and their distribution as a histogram (see figure 4). |

In order to generate the contours (step c in table 1) an algorithm called “Snakes”, or “Active Contour Tracking” was used [34]. This algorithm tracks contours in an image. The algorithm minimizes the distance between an object edge in an image and the generated curve, minimizes bending radii and keeps the contour and its first and second derivatives continuous.

The normal vectors were calculated as below:

The contour coordinates are stored in a 2D-vector

\[ X = \begin{pmatrix} x_1 & \cdots & x_N \\ y_1 & \cdots & y_N \end{pmatrix}, \]

and the tangent vectors \( TV \) are calculated as:

\[ TV_i = X_{i+3} - X_{i-3}, i = 3..N - 3. \]  

(1)

running in the positive X-direction, i.e.,

\[ TV = \begin{pmatrix} tvx_1 & \cdots & tvx_{N-6} \\ tvy_1 & \cdots & tvy_{N-6} \end{pmatrix} \]  

(2)

and the normal vectors are calculated as:

\[ NV = \begin{pmatrix} -tvy_1 & \cdots & -tvy_{N-6} \\ tvx_1 & \cdots & tvx_{N-6} \end{pmatrix} \]  

(3)

A low pass filtering effect was introduced by the indices i-3, i+3 in equation (1) The low pass filter reduces edge effects and reduces an otherwise low angular resolution. Seven pixels of filter length gives an angular resolution of \( \approx 8 \) degrees and will at the same time reduce contour noise and was chosen as a good balance between noise sensitivity and angular resolution.

It should be noted that when a 2D slice is taken from a 3D surface, it will sometimes result in isolated features that are not connected to any other features. In these experiments such isolated features have been excluded. An obvious extension of this technique is to generate contour tracking in 3D and present the surface normal vectors in a spherical format, but this is outside the scope of the present paper.

Figs. 5(a) and (b) demonstrate two types of overhanging feature which can be created by additive manufacturing and other droplet deposition techniques: Simple and Compound overhangs. An overhanging feature can be generally described as any object which would cast a shadow if exposed to a light shining directly down upon it. Within this category there are sub-categories which could be important to surface phenomena such as wetting. For example, figure 5(a) shows a cross section of a simple overhanging feature which might be generated by a single molten droplet attaching itself to a substrate. Depending on the geometry of this type of overhang, and the viscosity/surface tension of the liquid involved, it might be possible to fully wet all of this surface. Figure 5(b) on the other hand, shows a cross section of a more complex ‘compound’ overhang. In this case it would not be possible to entirely wet this surface because any encroaching liquid would find certain areas of the surface blocked by air bubbles trapped by the geometry of the compound overhang.
Figure 5. (a) A simple overhang surface profile, which might allow full surface wetting; (b) a ‘compound’ overhang surface profile, which would prevent full surface wetting due to trapped air bubbles; (c) surface normal vectors along the compound overhang surface profile. The presence of surface-normal vector angles greater than 270° degrees of or lower than -90° is indicative of a compound overhang. Angles in the ranges 0° to -90° (but no lower) or 180° to 270° (but no higher) indicate simple overhangs; (d) illustration of expressing the curve as a sum of linear sections $T_i$ each of equal length $\delta$, with corresponding surface normal vectors $N_i$ (starting at position $P_0$).

Compound overhangs cannot be adequately described or identified using a 0-360 degree scale for the direction of normal vectors which was employed in earlier work [28]. It is clear from figure 5(b) that, using a 360-degree scale, the shape of this compound overhang would, for example, give rise to two different types of area where the surface normal vector would be 270 degrees (i.e., vertically downwards). For this reason, we have developed the surface-normal vector angle analysis to include a range of angles greater than 360 degrees. figure 5(c) helps to provide an explanation of this approach. The assignment of angles to the surface normal vectors assumes that the surface contour is a line which is followed from its left-hand end to its right-hand end (i.e., in the positive x-direction). Surface normal vectors are calculated at equally spaced distances along this line. The angular value given to any vector is incrementally increased or decreased in comparison to the previous value depending on whether the normal vectors are progressing in an anticlockwise or clockwise direction. In this way two different numerical angular values will be given for the same surface-normal vector direction depending on what the previous vector value was. This allows us to differentiate between simple and compound overhangs. Figure 5(c) contains only the ordinal vectors (which are not equally spaced) to illustrate this point. In this example the initial change in vector angle is from 90 (vertically upwards) to 450 (also vertically upwards). Between these two points the angle continuously increases to 450 because the progression of vector angle values was anticlockwise. At the point at which the value of 450 degrees is reached the angle progression changes to clockwise and all subsequent angular values are continuously reducing until we reach the next vertically upwards vector (at the top of the object) which now has an angular value of 90 degrees. Comparison between figure 5(a) and figure 5(c) makes it clear that the limits on surface normal vector achievable by a simple (non-compound) overhanging feature using this system would be a highest value of 270 degrees and a lowest value of -90 degrees. Therefore, angles outside this range are indicative of the presence of compound overhangs. Table 2 summarises the angular ranges of surface-normal vectors for surfaces with no overhangs, simple overhangs, and compound overhangs.

Table 2. Angular ranges of surface-normal vectors for different surface features.
| Surface feature type   | Surface-normal vector inclination range          |
|-----------------------|-------------------------------------------------|
| No overhangs          | 0° to 180°                                      |
| Simple overhangs      | -90° to 0° and/or 180° to 270°                 |
| Compound overhangs    | Below -90° and/or above 270°                   |

Figure 6 shows a typical result from the raw Additive Manufacturing sample investigated in this work as an example of how to interpret the surface-normal vector histograms which will be presented in the results section. The thresholds for simple and compound overhangs, see Table 2, are both exceeded in this example showing that both types of overhang are present on the surface. This is confirmed by observation of the black and white image of the cross section at the top of the figure.

One of the aims of this work is to develop tools which could be used to identify repeating patterns in the surface roughness which might be correlated to process parameters. For example, the Biohelix process produces a regular pattern of laser surface melts. If we consider the surface profile to be a signal then frequency analysis should reveal this repeating pattern. However, this simple approach is not possible in this case because, when overhangs are involved, the ‘curve’ of the surface trace sometimes includes two or more \( y \) values for the same \( x \) value, i.e., it has ambiguous coordinates. For a standard frequency (Fourier or Laplace) analysis it is important that the curve in question is single valued, i.e., unambiguous.

One way to get around this problem is not to express the profile curve not as \( y = f(x) \) but to divide it up into a succession of linear segments – as shown in figure 5(d).

If the profile curve is divided up into short straight lines each of equal length \( \delta \), pointing in the tangential direction (see figure 5(d)), the position at a point \( P_i \) on the curve, can then be expressed as:

\[
\vec{P}_i = \vec{P}_0 + \sum_{k=0}^{\infty} \delta \vec{T}_k
\]

Calculating the normal vectors from the tangents and plotting normal vector angle vs. position now gives a single-valued set of data which is suitable for frequency analysis.

3. Results and Discussion

3.1 General comparison of sample surfaces

Figure 7 presents Micro-CT images of the four sample surfaces. Certain features of the surfaces are clear:

- The grit blasted surface has the smoothest surface.
- The BioHelix surface was produced as a pattern of parallel overlapping lines (like a ploughed field) Olsson.[27]

The AM surface (c) and its etched counterpart (d) have larger surface features than the BioHelix sample and the grit blasted sample.

**Figure 6.** Surface profile (raw AM) with compound overhangs (upper) and its histogram (lower) with thresholds of the angle ranges for no, simple and compound overhang, respectively.
Slices through the Micro-CT data can now be taken, giving cross sections from which the surface profile and its normal vector at any point can be identified. Following the procedure laid out in table 1 and figure 4, figure 8 presents typical profile cross sections of the four samples together with the histograms of the surface-normal vector distributions.

The span of surface-normal vector inclinations and their standard deviations are presented in Table 3 together with the relevant $R_a$ roughness measurements. Figure 8(a) confirms the assumption that grit blasting does not create overhanging features in a surface. In this case the range of surface-normal vector inclinations is only 85 degrees; from 50 to 135, with a standard deviation of only 16 degrees. In the case of the BioHelix sample, figure 8(b), the range of vector angles is much wider; from -122 degrees to 160, with a standard deviation of 59 degrees. The existence of angles below -90 clearly indicates that there are simple and compound overhanging features on this surface. The presence of such features is obvious in the SEM image of this surface presented in figure 9. The BioHelix process produces a micro-rough surface which is optimised for osseointegration. The distinctive surface texture is achieved by producing a ‘splashy’ surface of parallel, overlapping rows of shallow melts that experience melt disruption during processing [27,28]. This gives a complex surface containing overhangs.
Table 3. Statistical surface properties (surface-normal angle range and roughness) of the four surfaces.

| Surface       | Standard deviation of angles (°) | Angular range (°) of surface-normal vectors. | $R_a$ (µm) |
|---------------|---------------------------------|---------------------------------------------|------------|
| Grit-blasted  | 16                              | 50 to 135                                   | 1.5        |
| Laser BioHelix| 59                              | -122 to 160                                 | 2          |
| Raw AM        | 52                              | -190 to 270                                 | 24         |
| Etched AM     | 79                              | -153 to 321                                 | 16         |

Figure 9. This higher magnification SEM image of the laser BioHelix sample surface reveals the presence of overhanging features.

As might be expected the Raw Additive Manufacturing surface figure 8(c) also has a considerable number of overhanging features, surface-normal vector angles from -190 to 270 degrees. The overhanging features of the AM surface are created by the impingement of overlapping laser-melted droplets. It is important to note that the results indicate that the level of overhanging features on a surface is not related to $R_a$ roughness (see Table 3).

Figure 8(d) shows the strong evidence of overhanging features for the etched AM surface, with an inclination angle range of between -153 and 321 degrees. Further investigation of this surface (compare Figs. 8(c) and (d)) indicates that the zinc chloride etchant has corroded and undermined the overhanging features created by the AM droplet deposition process.

3.2 Directional roughness analysis

The next stage in our analysis of these surfaces was to investigate the differences between tomography cross sections taken in different directions across the sample surface. Slices from each sample were taken using the ParaView-software [35] at four different angles; 0°, 45°, 90° and 135°, as shown in figures 10(a)-(d).

Figure 10. The four chosen slicing orientations to extract surface profiles from 3D-data measured by Micro CT: (a) 0°, (b) 45°, (c) 90°, (d) 135°.
The sliced results for the four directions in each of the four samples are presented in Figs 11-14.

**Figure 11.** Grit blasted sample; (a) surface profiles and (b) normal vector angle distribution for the four slicing angle orientations; the angle limits for simple and compound overhang are highlighted.

**Figure 12.** BioHelix sample; (a) surface profiles and (b) normal vector angle distribution for the four slicing angle orientations; the angle limits for simple and compound overhang are highlighted.

**Figure 13.** Raw AM sample; (a) surface profiles and (b) normal vector angle distribution for the four slicing angle orientations; the angle limits for simple and compound overhang are highlighted.
Figure 14. Etched AM sample; (a) surface profiles and (b) normal vector angle distribution for the four slicing angle orientations; the angle limits for simple and compound overhang are highlighted.

Figure 11 shows no noticeable trends between the cross section directions, with a low level of roughness and low levels of inclination of the surface normal vectors. There are no vector angles below zero or above 180 and so no overhanging features of any sort are present. This is the expected result from a random roughness grit blasted surface. Figs. 13 and 14 also show minimal evidence of differences in profile or normal vector distribution between the four different sampling directions. For these samples there is evidence of simple and compound overhangs in both the cross section images and the vector histograms. Figure 13 generally has a cluster of vector direction at 90 degrees which is not as distinct in the case of figure 14. This indicates that the AM surface has a flatter surface than the etched AM sample.

Figure 12 is the only sample which shows clear directional differences between the traces, i.e. anisotropy. The BioHelix sample shows evidence of simple and occasional compound overhangs but also appears to have a repeating pattern within the general roughness in certain cross sectional directions. This makes sense because the surface is generated from parallel rows of surface ‘splashes’ created at a pitch of 59 µm between laser pulses.

3.3 Quantification of overhang levels

The final stage in this work was to estimate how much of the surface would be shadowed by overhanging features if illuminated from directly above (i.e., how much of the surface is involved in overhanging features). This was calculated by establishing the proportion of surface-normal vectors which were above the inclination thresholds for simple and compound overhangs.

The results are presented in Table 4.
Table 4. The proportion of the sample surface covered by simple and compound overhangs expressed as a percentage of the width of the sample, for the four slicing angles.

| Trace angles (°) | 0  | Proportion of simple overhang (%) | Proportion of compound overhang (%) |
|------------------|----|----------------------------------|-----------------------------------|
|                  | 45 |                                  |                                   |
|                  | 90 |                                  |                                   |
|                  | 135|                                  |                                   |
| (a) Grit-blasted | 0  | 0                                | 0                                 |
|                  | 45 | 0                                | 0                                 |
|                  | 90 | 0                                | 0                                 |
|                  | 135| 0                                | 0                                 |
| (b) Laser - BioHelix | 0.4 | 0                                | 0                                 |
|                  | 2.5 | 0                                | 0                                 |
|                  | 2.4 | 0.4                              |                                   |
|                  | 0.8 | 0                                |                                   |
| (c) Raw AM       | 28 | 0                                | 0                                 |
|                  | 36 | 1                                |                                   |
|                  | 18 | 1.6                              |                                   |
|                  | 14 | 2.7                              |                                   |
| (d) Etched AM    | 41 | 0.4                              |                                   |
|                  | 43 | 7.0                              |                                   |
|                  | 19 | 0                                |                                   |
|                  | 49 | 0                                |                                   |

Table 4 reveals the following points; Once again we can see that there are no overhanging features on the grit blasted surface. The laser-Biohelix surface has evidence of simple overhanging features with a small amount of compound overhangs. Approximately 25% of the Raw AM surface is covered by simple overhangs and, on average, 1.25% of the surface involves compound overhangs. In the case of the etched AM surface approximately 40% of the surface is covered in simple overhangs with 2% of the surface having compound overhangs. This could be expected because of etchant corrosion undermining the overhangs created by the AM process.

3.4 Advantages and limitations of the technique
The surface analysis technique presented here has the advantages that features which are hidden from optical and mechanical methods can be included in qualitative and quantitative assessments. Deeply complex surfaces can be described, and the method is essentially size-independent. The technique could be expanded into 3D and Standard Tessellation Language (STL) models can be used.

Limitations of the technique include the fact that it involves expensive equipment and sampling which is not non-destructive. Also, it is not appropriate in cases where the features under investigation are of a similar, or larger, scale to the specimen size used for Micro-CT.

3.5 Future work
In future work the algorithms developed here to study overhanging features need to be tested for the limits of their applicability and generalisation. This would lead on to full three-dimensional spatial analysis involving even more complex overhangs and surface features.

The rapid growth in additive manufacturing and laser surface texturing means that technical surfaces with overhanging features are likely to become more common. Future work on the characteristics of such surfaces will depend on the type of analytical tools presented here for the quantitative assessment of overhanging features.
4. Conclusions

- Additive manufacturing and laser surface texturing can create surfaces covered in overhanging features; this can have substantial effects on surface properties such as wettability.
- Overhanging features can usefully be divided into two types: simple and compound.
- Micro-CT can reveal the topological details of convoluted surfaces containing both simple and compound overhangs.
- From micro-CT results surface profiles can be extracted; surface-normal vectors can be applied to these profiles along with an angle-based algorithm to quantitatively identify the presence and proportion of simple and compound overhangs; different characteristics were demonstrated for four surfaces.
- Studying surface profiles in different directions facilitates the identification of topological anisotropies.
- Convoluted surface profiles containing overhanging features cannot be subjected to standard Fourier analysis to search for repeating patterns because they have ambiguous vertical coordinates. However, frequency analysis can be used if the surface is divided up into a series of short, straight-line segments with surface-normal vectors.
- Analysis tools of this type will become increasingly useful as surfaces including overhangs generated by lasers and other technologies become more common.

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