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# Generalization of area-scale analysis for complex additively manufactured freeform surfaces

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**Abstract**

Additively manufactured metal surfaces often exhibit complex freeform morphologies with re-entrant features that cannot be represented as single-valued height maps, limiting the applicability of conventional surface texture analysis. This work presents a generalized area-scale analysis framework that extends the classical area-scale concept to three-dimensional surface meshes derived from X-ray micro-computed tomography. The method enables robust multiscale characterization of surfaces containing undercuts, overhangs, and partially fused particles. The approach was applied to selectively laser melted Ti-6Al-4V parts produced using varied laser power and scanning speed. Strong, scale-dependent correlations were identified between process parameters and surface morphology. Relative surface area showed strong dependence on laser power ($R^2 > 0.6$ for scales ≥ 4,050 μm²), while surface complexity, quantified by the fractal dimension $D_{as}$, was primarily governed by scanning speed ($R^2 = 0.817$). These results demonstrate that the proposed method captures both surface development and hierarchical organization in a physically interpretable manner. The generalized area-scale framework provides quantitative insights not accessible through conventional roughness parameters or height-map-based analyses and offers a unified basis for linking additive manufacturing process conditions with multiscale surface geometry, supporting process optimization and functional surface design.

Multiscale analysis, X-ray micro-computed tomography, additive manufacturing, area-scale analysis

## 1. Introduction

Area-scale analysis, standardized in ISO 25178-2 [1] and ASME B46.1 [2], is a powerful and well-established tool for multiscale characterization of surface topographies. By evaluating the relative surface area as a function of scale, it enables quantitative assessment of surface development and geometric complexity across multiple length scales [3]. However, its conventional formulation fundamentally relies on a single-valued surface representation, where each in-plane location $(x, y)$ corresponds to exactly one height value $z$ [4].

This assumption significantly limits the applicability of area-scale analysis to a wide class of surfaces encountered in modern manufacturing. In particular, additive manufacturing (AM) processes such as selective laser melting (SLM) produce surfaces with highly complex morphologies that cannot be described as single-valued height maps [5]. These surfaces are best described as freeform geometries, containing a multitude of re-entrant features, including overhangs, undercuts, partially fused powder particles, and enclosed cavities [6–8]. Such features violate the $z = z(x, y)$ condition and are therefore incompatible with standard area-scale implementations [9].

At the same time, these re-entrant surface morphologies are not merely geometric artefacts but play a critical role in functional performance. They influence wettability [10], adhesion [11], heat transfer, fatigue behavior [12,13], and biological response [14], particularly in applications such as heat exchangers and biomedical implants [15]. Accurate and scale-sensitive characterization of these freeform surfaces is therefore essential for understanding and controlling AM process–structure relationships.

In this work, we propose a generalization of area-scale analysis for freeform surfaces that explicitly accommodates geometries with re-entrant features where there can be more than one height at each location. The proposed approach operates directly on three-dimensional surface representations obtained from high-resolution X-ray micro-computed tomography, bypassing the limitations of height-map-based methods. By extending the area-scale concept to mesh-based surface descriptions, the method enables the quantification of surface development and fractal complexity for additively manufactured freeform surfaces across a wide range of scales. Consistent with Brown [16], who argues that meaningful surface metrology depends on identifying strong functional correlations through scale-sensitive analyses and the use of geometric characterizations that are directly pertinent to the underlying physical interactions, this study adopts a multiscale, geometry-driven perspective on surface texture.

## 2. Materials and methods

### *2.1. Test surface and manufacturing parameters*

The study was conducted on twenty additively manufactured parts produced using the laser powder-bed fusion process. All parts were fabricated from Ti-6Al-4V titanium alloy powder with a particle size distribution of 15–45 µm, a material widely used in aerospace and biomedical applications due to its high strength-to-weight ratio and biocompatibility.

Each specimen had identical nominal geometry in the form of a quarter-cylinder with a height of 25 mm and a radius of 5 mm, ensuring that observed differences in surface morphology were solely attributable to process parameters. The parts were manufactured on an EOS M290 system using twenty distinct combinations of laser power and scanning speed. Laser power was varied from 107 W to 267 W in incremental steps of 40 W, while scanning speed ranged from 250 mm/s to 1000 mm/s in steps of 250 mm/s. This parameter matrix enabled systematic investigation of the individual and combined effects of energy input and scan dynamics on surface morphology.

### *2.2. Surface acquisition using X-ray micro-computed tomography*

Due to the presence of re-entrant and multi-valued surface features, conventional optical or tactile surface measurement techniques were unsuitable for accurate surface acquisition. Therefore, all parts were measured using metrological X-ray micro-computed tomography (µCT). The scanner used here was Baker Hughes/General Electric v|tome|x s240. The voxel size was 5.5 µm.

The µCT measurements provided full volumetric reconstructions of each specimen, capturing undercuts, overhangs, and enclosed features that are inaccessible to line-of-sight methods. The reconstructed data were exported as STL surface meshes, preserving the true three-dimensional geometry of the surfaces. To ensure computational tractability, each surface mesh, originally consisting of several million triangles, was subdivided into smaller regions prior to analysis.

### *2.3. Generalized area-scale analysis*

A generalized area-scale analysis framework was developed to enable multiscale characterization of freeform surfaces with re-entrant geometries. Unlike the conventional area-scale method defined for height-map representations, the proposed approach operates directly on three-dimensional surface meshes.

The surface was partitioned into a set of triangular patches of constant area across a range of predefined scales. For each scale, cross-sectional slicing of the surface mesh was performed, followed by triangulation and mesh-based approximation of the local surface geometry. The distance *d* between two adjacent cross-sectional profiles was associated with scale *s* so that $s=0.5\times d^2$. The computations were performed for *d* between 5 and 150 µm with an increment of 5 µm (*s* ranging between 12.5 11,250 µm$^2$). The patchwork algorithm was performed for all pairs of adjacent profiles following the original algorithm by Brown et al. [4]. The relative surface area was then calculated as the ratio of the true surface area represented by the triangular patches to the projected or nominal reference area. Reference area was considered flat.

By repeating this procedure over multiple scales, an area-scale relationship was obtained and represented in log–log space. The fractal dimension $D_{as}$ was determined from the slope of the linear region of the log–log plot, in accordance with the principles of ISO 25178-2[1]. All data processing and analysis steps were implemented in a custom algorithm developed in Python, ensuring repeatability and consistency across all samples.

The calculated parameter Srel was regressed linearly with laser power and scanning speed independently. The strengths of correlations, denoted as $R^2$, were plotted as a function of scale to reveal the scale-dependent interactions between formation parameters and resulted surface texture. Fractal dimensions were also regressed linearly. Non-linear quadratic model was used to associate both technological parameters with $D_{as}$ and $S_{rel}$ at a particular scales of observations.

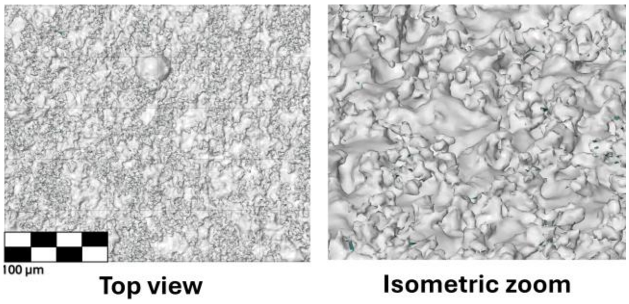


**Figure 1.** Exemplary surface views of studied parts with evident re-entrant features

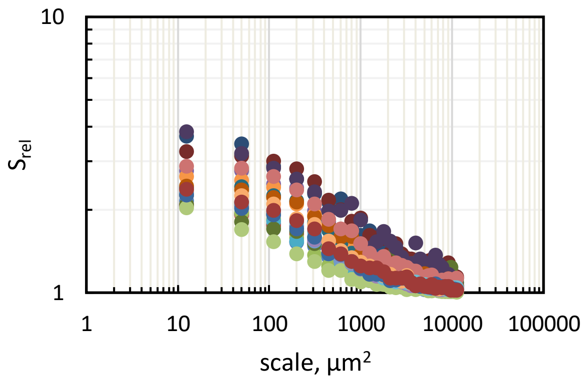


**Figure 2.** Evolution of relative area $S_{rel}$ as a function of scale for 20 studied surfaces

## 3. Results

### *3.1. Relative surface area*

The presence of re-entrant features in studied surfaces is strong and evident (Figure 1). The shape and size of re-entrant formations appear to differ depending on the particular part. The exemplary relation of relative area $S_{rel}$ as function of scale calculated for all 20 studied surfaces is shown in Figure 2. It can be noted that the values tend to converge to 1.0 as the scale gets larger but the trends are different depending on the particular surface. It should be noted that for the finest scales relative area exceed 2.0. This is due to the presence of re-entrant geometries which add additional area to the calculation of total area.

The relative surface area $S_{rel}$ showed a strong and systematic dependence on laser power. This effect was evident for scales greater than or equal to 4,050 µm$^2$ ($R^2$>0.6) as seen in Figure 3. Increasing laser power led to higher values of $S_{rel}$ across all analyzed scales and scanning speeds. This behavior indicates enhanced surface development at higher energy input, consistent with increased melt pool size and intensified adhesion of partially melted powder particles.

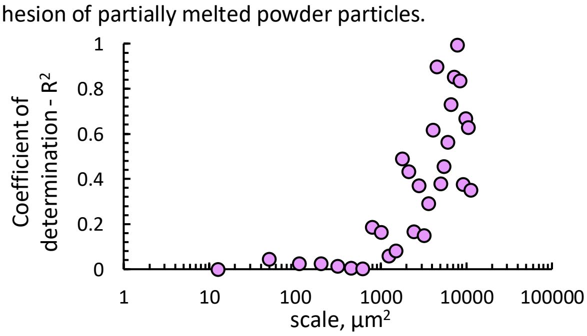


**Figure 3.** Strengths of linear correlation between relative area $S_{rel}$ and laser power as a function of scale

The effect of scanning speed on $S_{rel}$ was comparatively weaker but still moderately strong. It was noted that changes in scanning speed produced decreasing relation across the full parameter range. This was observed also for the larger scales starting from 4,050 µm² ($R^2$>0.6) as depicted in Figure 4. These results indicate that surface development, as quantified by area-scale analysis, is also governed by scanning speed.

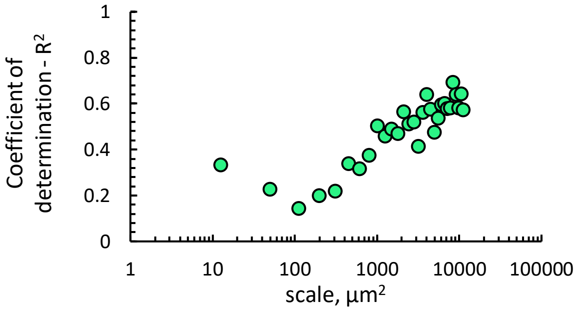


**Figure 4.** Strengths of linear correlation between relative area $S_{rel}$ and scanning speed as a function of scale

### *3.2. Fractal dimension*

The fractal complexity parameter $D_{as}$, obtained from the slope of the area-scale curves in log–log space, exhibited a strong dependence on scanning speed ($R^2$=0.817). As demonstrated in Figure 5, increasing scanning speed resulted in a systematic increase in $D_{as}$, indicating a prevalence in geometric complexity at higher scan velocities. This means that the surface becomes more self-affine as the scanning speed increases, resulting in less intense local heat transfer.

The influence of laser power on $D_{as}$ was also strong ($R^2$=0.719). As shown in Figure 6, higher laser power produced only moderate changes in complexity, suggesting that power affects the magnitude of surface growth rather than the hierarchical, self-similar organization of surface features.

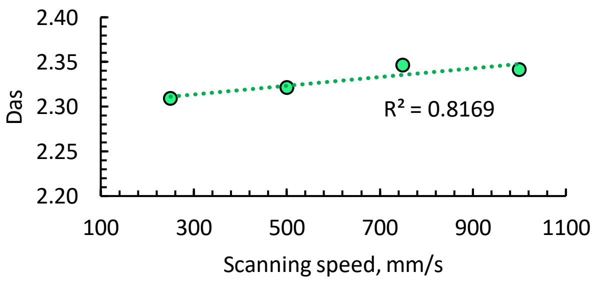


**Figure 5.** Fractal dimension as a function of scanning speed

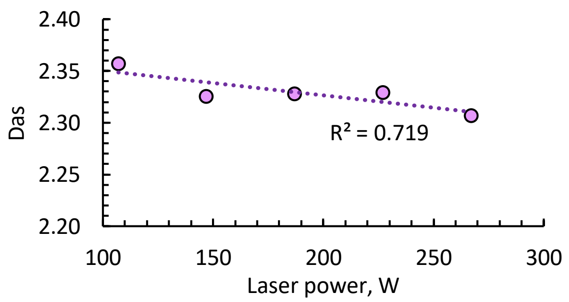


**Figure 6.** Fractal dimension as a function of laser power

### *4.3. Combined effects of process parameters*

The combined influence of laser power and scanning speed on surface fractal dimensions is visualized in Figure 7. These results reveal a clear separation of parameter roles, low laser power and high scanning speed lead to the greater fractal dimension. At this manufacturing conditions the powder is fused at the lowest heat intensity, meaning that the resulting surface morphology is the product of the metal powder geometry. Manufacturing at the slowest scanning speed and highest laser power ends with intense powder melting and the formation of less self-affine structures.

The strengths of correlation between combined technological parameters and relative area is dependent on the scale of observation. Strongest correlations were observed starting from the scale of 4,050 µm² , as shown in Figure 8 (left). The effect of laser power is the most noticeable at the slowest and the fastest scanning speeds. No correlations were found at the finest range of scales as depicted in Figure 8 (right).

Overall, the results demonstrate that the generalized area-scale analysis is sensitive to both surface growth and multiscale structural organization, enabling quantitative differentiation of the effects of key powder-bed fusion process parameters on freeform, re-entrant surface morphologies.

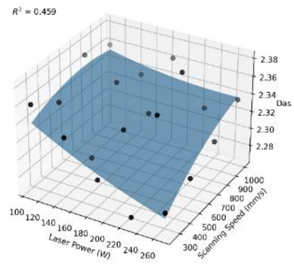


**Figure 7.** Fractal dimension as a function of laser power and scanning speed.

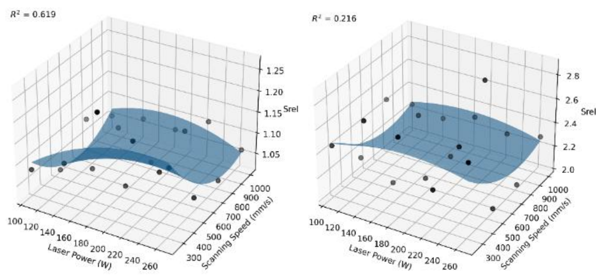


**Figure 8.** Relative area as a function of laser power and scanning speed calculated at scale equal to 4,050 µm² (left figure) and 12.5 µm² (right)

## 4. Discussion

This study shows that area-scale analysis can be successfully generalized to freeform, re-entrant surfaces measured by µCT, enabling multiscale characterization beyond the limitations of single-valued height maps. The stability of the area–scale relationships confirms that relative surface area remains meaningful when extended to freeform geometries with evident re-entrant features.

The observed effects of process parameters are consistent with earlier work on the same parts using multiscale curvature analysis [5]. In both studies, correlations with processing conditions are strongest at larger scales, while fine scales associated with powder particle size show little sensitivity. Laser power primarily governs surface development, reflected here by changes in relative area, whereas scanning speed more strongly affects geometric complexity, captured by fractal dimension. This agrees with the curvature-based finding that scanning speed controls shape complexity while laser power mainly influences the magnitude of surface formation. Thus, both methods converge on a common physical interpretation of the L-PBF process.

Compared with curvature analysis, the generalized area-scale approach provides complementary information. Curvature describes local shape without requiring a datum [17], whereas area-scale analysis quantifies global surface development, explicitly capturing the contribution of re-entrant features to total surface area. This makes the method particularly relevant for functional properties linked to surface enlargement, such as wettability, adhesion, and biological response.

The main strengths of the proposed method are: (i) its direct applicability to re-entrant geometries, (ii) its ability to distinguish between surface development and hierarchical self-similar organization within a single framework, and (iii) its clear physical interpretability in terms of melt pool dynamics and energy input. However, the approach is computationally more demanding than profile-based methods, depends on mesh quality and segmentation of µCT data, and shows limited sensitivity at the finest scales where substrate powder geometry dominates. It also requires fine resolution scanning which limits the application to small-size objects. In addition, relative area provides a global measure of surface development but does not describe local feature morphology in detail.

The fact that the strongest correlations were observed starting at a scale of 4,050 µm², corresponding to the spacing distance *d* equal to 90 µm, is particularly significant from a process–physics perspective. This characteristic scale is very close to the effective laser spot radius used during manufacturing (approx. 100 µm), suggesting that the generalized area-scale analysis becomes most sensitive when the observation scale matches the dominant length scale of energy input in the L-PBF process. At this scale, surface morphology is no longer governed primarily by individual powder particles or voxel-level measurement noise, but by melt pool geometry, resolidification behavior, and material redistribution induced directly by the laser beam. Strong correlations of similar nature were also found by Lemoine et al. who studied Inconel alloy 718 and the effect of linear energy density on relative area and fractal complexity [18]. They used optical microscopy which cannot capture re-entrant geometries but they found that process parameters correlated strongly starting also at large scales (>7,000 µm²).

Overall, the results demonstrate that generalized area-scale analysis complements existing multiscale methods for freeform AM surfaces. Together with curvature-based approaches, it offers a robust framework for linking additive manufacturing process parameters with multiscale surface geometry and supports more informed surface engineering.

## 5. Conclusion

This work introduces a generalized area-scale analysis framework for the characterization of complex freeform surfaces produced by additive manufacturing. By extending the conventional area-scale concept beyond single-valued height representations and applying it directly to three-dimensional surface meshes obtained from X-ray micro-computed tomography, the proposed method enables consistent multiscale analysis of surfaces containing re-entrant geometries. Application of the method to selectively laser melted Ti-6Al-4V parts revealed clear and physically interpretable relationships between process parameters and surface morphology. Laser power was identified as the primary factor controlling surface development, reflected in strong linear correlations with relative surface area ($R^2 > 0.6$) for scales above 4,050 µm², while scanning speed predominantly governed surface complexity and hierarchical organization, as captured by the fractal dimension $D_{as}$ ($R^2 = 0.817$). The influence of laser power on $D_{as}$ was also significant ($R^2 = 0.719$), confirming distinct but complementary roles of both parameters.

These results demonstrate that the generalized area-scale approach yields quantitative insights that are inaccessible to conventional roughness parameters and height-map-based analyses. The method provides a unified framework for linking additive manufacturing process conditions with multiscale surface geometry and shows strong potential for process optimization and the design of functionally tailored surfaces in advanced manufacturing.

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