Surface roughness optimisation for selective laser melting (SLM): accommodating relevant and irrelevant surfaces

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4.1 Introduction

Additive manufacturing (AM) provides a significant opportunity for the manufacture of innovative products. In particular, AM allows the manufacture of geometries that include complex features that are not possible with traditional manufacturing methods, and the opportunity to economically manufacture short production runs without significant cost penalty. In particular, AM is suited to the manufacture of:

- prototype components, for design validation before large-volume manufacture
- low-volume production components, especially during the initial deployment of a specific design, to allow rapid implementation of design changes, as required
- high-volume customised components for which the geometry of each component is subject to variation and is therefore not compatible with fixed-tooling methods
- components that are not technically feasible with traditional methods, for example, complex lattice structures and components with internal voids

For these scenarios, it is likely that surface roughness is a highly relevant design attribute. For AM, surface roughness is highly dependent on the specific attributes of the AM process used, the associated process parameters, and the orientation of the component within the available build volume.

To provide AM components that are acceptable for a specific purpose, a quantified surface roughness is highly desirable; the available literature includes work that seeks to address this issue, including experimental investigation of surface roughness of selective laser melting (SLM) [1–6], fused deposition modelling [7–10], and selective laser sintering [11]. The orientation of the component can be used to optimise the average surface roughness. Orientation is optimised by reference to either pre-selected [7,12] or continuously variable orientations [13–15]. This work contributes to the available literature by providing:

- New material roughness data: To provide useful design data, the surface roughness versus build inclination of SLM Ti64 is experimentally assessed and reported in detail, including high-magnification microscopy and associated surface roughness statistics of the upper and lower surfaces for a comprehensive array of specimen inclinations.
• **Visualisation of roughness objectives versus orientation**: An infinite number of feasible orientations of a component exist within the build volume. Visualisation of the roughness objectives within the assessed orientations aids identification of the optimal orientation(s) within the available optimisation time.

• **Novel surface roughness objectives**: The available literature on orientation optimisation considers only the minimisation of average surface roughness. This research proposes novel surface roughness objectives, including:
  - *peak roughness avoidance*, which is appropriate when a specific roughness type violates an inflexible design constraint.
  - *weighted roughness*, which is appropriate when a non-linear correlation exists between specific roughness types and performance.

• **Filtering of irrelevant surfaces**: It is common for a manufactured product to include surfaces that are irrelevant in terms of associated surface roughness. For example, commercial products consist of *visible* and *hidden* surfaces. Hidden surfaces are not relevant to the aesthetic value associated with the product. Engineering components may have critical roughness tolerances associated with key surfaces, but not all surfaces are functionally relevant. The method proposed in this research enables the discrimination of relevant and irrelevant surfaces when assessing the associated surface roughness objective.

These contributions have been used to enable novel design outcomes for a number of engineering applications of SLM technologies (Section 4.4):

• **A surgical implant**, whereby an orientation map of average roughness is presented for feasible orientations to identify the optimal implant orientation for surgical objectives

• **Low-volume prototype cover**, whereby a custom roughness weighting is applied to discourage facets with high roughness from occurring on visible surfaces

• **Hydraulic valve assembly**, whereby surfaces of relevance to functional objectives are assessed to enable robust identification of optimal build orientation

### 4.2 Additive manufacturing

AM is defined by the ASTM [16] as the ‘process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies, such as traditional machining’. AM begins with a computer-assisted design (CAD) representation of the intended component geometry. This data are then converted to stereolithographic (STL) format to be compatible with AM processes (Fig. 4.1). The STL format represents the CAD data with a discrete number of triangular facets and their associated surface norms (Table 4.1). The STL representation is processed as required to provide specific tool path and processing instructions for the specific AM method [17,18].

AM processes can be characterised according to the method by which support is provided, the resolution of the manufactured geometry to the intended geometry, and the relevant processing parameters of manufacture [18–20]. Of the AM processes of commercial interest, SLM is extremely important because it allows the manufacture of large-scale functional components with engineering-grade metals with high complexity and a relatively low unit cost [21]. This research focuses specifically on the optimisation of SLM components with specific surface finish objectives; however, the associated methods are generally applicable to any AM processes.
Figure 4.1 Computer-assisted design model (shaded) and associated stereolithographic representation (wireframe facets). This model of a low-volume prototype cover indicates visible (A-class) and non-visible (B-class) surfaces, which inherently have different surface roughness objectives.

Table 4.1 Binary stereolithographic file standard

<table>
<thead>
<tr>
<th>Element</th>
<th>Content</th>
<th>Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Header</td>
<td>Component information</td>
<td>80 bytes</td>
</tr>
<tr>
<td>$n$</td>
<td>Number of facets</td>
<td>32-bit unsigned integer</td>
</tr>
<tr>
<td>Facet $i$</td>
<td>Vertex 1 Cartesian coordinates</td>
<td>32-bit floating point</td>
</tr>
<tr>
<td></td>
<td>Vertex 2 Cartesian coordinates</td>
<td>32-bit floating point</td>
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<tr>
<td></td>
<td>Vertex 3 Cartesian coordinates</td>
<td>32-bit floating point</td>
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<tr>
<td></td>
<td>Facet normal vector</td>
<td>32-bit floating point</td>
</tr>
<tr>
<td></td>
<td>Attribute byte count</td>
<td>2-byte unsigned integer</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Facet $n$</td>
<td>Vertex 1 Cartesian coordinates</td>
<td>32-bit floating point</td>
</tr>
<tr>
<td></td>
<td>Vertex 2 Cartesian coordinates</td>
<td>32-bit floating point</td>
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<tr>
<td></td>
<td>Vertex 3 Cartesian coordinates</td>
<td>32-bit floating point</td>
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<td></td>
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<td>2-byte unsigned integer</td>
</tr>
</tbody>
</table>
4.2.1 Selective laser melting

SLM refers to the fusion of metal powder with a laser power source to incrementally manufacture an intended product [22]. SLM is an important commercial AM process because it [21,23]:

- enables the manufacture of a range of fusible ferrous and non-ferrous metals
- readily accommodates support structures to enable manufacture of acute overhang geometry
- provides high structural integrity of manufactured components
- has relatively low fixed and variable costs
- has a reasonably short build time

Despite the particular advantages associated with SLM, the associated surface roughness may introduce technical challenges because of the layered nature of AM and the associated process parameters and powder morphology.

Control of surface roughness is of particular importance for commercial applications because of the associated implications on product aesthetics, structural integrity and geometric tolerance. Surface roughness is fundamentally the result of some source of geometric error.

4.2.2 Sources of geometric error

Geometric error refers to a discrepancy between the CAD representation of the intended product and the geometry of the actual manufactured product. Geometric error in AM can be attributed to either error in the STL representation of the CAD geometry or error in the AM manufacture of the STL representation (Fig. 4.2).

4.2.2.1 Error in STL representation of CAD data

Because of the discrete nature of the STL format, error may occur in the representation of the original CAD data. If the original CAD data are prismatic, the discrete facets of the STL represent the CAD data without error (Fig. 4.1). If the original CAD data are

![Figure 4.2](image)

Figure 4.2 Layered approximation of computer-assisted design (CAD) geometry, indicating a loss of fidelity between the CAD and the manufactured geometry as a result of staircase error [24].
curvilinear, the STL representation of the original CAD data includes some approximation error (Fig. 4.2); this error diminishes with an increasing number of facets [6]. It is desirable to minimise the number of facets to reduce computational demands; if possible, however, the number of facets should be sufficiently high that the associated STL representation error is negligibly small.

4.2.2.2 Error in manufacture of the STL representation

AM involves the successive addition of material to manufacture an intended geometry. The AM process introduces manufacturing error in the representation of the STL data as a result of:

1. machine precision and repeatability [25]
2. distortion and part shrinkage [6]
3. staircase errors [9,26], which introduce roughness caused by the discrete layers associated with AM (Fig. 4.2)
4. Roughness introduced by process parameters, the laser scan path [6], and the powder morphology [4]

4.3 Roughness

Roughness refers to a geometric deviation from a reference datum. Numerous measures of roughness have been proposed [27]. To be compatible with other contributions in this field, the arithmetic average roughness, \( R_a \), is used, where \( R_a \) measures the arithmetic average deviation of the measured profile from the centre line of the measured profile (Eq. (4.1)):

\[
R_a = \frac{1}{n} \sum_{i=1}^{n} |y_j|
\]  

(4.1)

where \( y_j \) is the vertical distance from the mean line to the \( j \)th data point and \( i \) is the facet of interest.

4.3.1 Experimental results

Specimens were fabricated to quantify the roughness of a commercial SLM method versus inclination angle\(^1\) (Table 4.2, Fig. 4.3). Optical macroscopy was recorded (Fig. 4.5) and \( R_a \) recorded for the upper and lower surfaces (Fig. 4.6).

Inspection of the sample macroscopy (Fig. 4.5) and measured surface roughness (Fig. 4.6) identifies distinct topology regions associated with the inclination angle \( \Phi \):

- For inclinations approaching horizontal (\( \phi \to 0 \) degree), staircase effects dominate, and the observed roughness asymptotes towards peak values. For inclinations below the

\(^1\) Note, the inclination angle, \( \phi \), used in this work seems to be the most common nomenclature reported in the literature; however, \( \theta = \pi/2 - \phi \), for example, is also used [8].
Table 4.2 Process parameters associated with the samples shown in Fig. 4.4

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Machine Specification</td>
<td>SLM Solutions 250HL</td>
</tr>
<tr>
<td>Layer thickness</td>
<td>30 μm</td>
</tr>
<tr>
<td>Ambient temperature</td>
<td>90°C</td>
</tr>
<tr>
<td>Process parameters</td>
<td>As in Ref. [28]</td>
</tr>
<tr>
<td>Powder Material</td>
<td>Ti64</td>
</tr>
<tr>
<td>Size distribution</td>
<td>See Fig. 4.4</td>
</tr>
</tbody>
</table>

Figure 4.3 Standard specimens to assess surface roughness versus inclination angle, φ. α and β refer to the perpendicular direction of roughness measurement.

Figure 4.4 Ti64 powder distribution.
self-supporting inclination angle, supporting structures may be desirable to reduce error during manufacturing.

- As the surface tends towards a vertical orientation, $\phi \to 90$ degrees, the staircase effects coalesce, and observed roughness seems to be predominantly the result of the presence of adhered, partially melted particles.

- Of the curve fit options considered (linear, exponential, power, and logarithmic), the correlation of the logarithmic curve provides the best match for both the upper and lower surfaces (Table 4.3); although the variability associated with the logarithmic curve fit shown in Fig. 4.6 is relatively high, it does provide a useful insight into observed roughness trends.

- The observed roughness in the lower surface is always larger than that of the upper surface, and often significantly larger. The rationale for this observation is that heat transfer through the inclined specimen causes elevated temperatures at downward-facing (lower) surfaces, resulting in greater thermal distortion and particle adhesion. Surface damage to downward-facing surfaces can also occur where supporting structures are physically removed from the surface, although no supporting structures were used to generate the coupons used in this research.

Figure 4.5 Macroscopy of SLM samples at inclination angles $\phi$ of 0–40 degrees (a) and 50–90 degrees (b). Orientation $\alpha$ and $\beta$ are as defined in Fig. 4.4.
By accommodating these observations of surface roughness versus surface inclination and by rotating the intended component according to the spatial rotations shown in Fig. 4.7, the associated surface finish can be optimised for the specific design objectives.

### 4.3.2 Roughness objectives

To achieve robust surface roughness outcomes in AM, it is critically important to apply a surface roughness objective that is appropriate for the intended functional and aesthetic objectives. In addition to the area-weighted average roughness, $R_{a_{ave}}$, that is reported in the literature, this section presents a series of novel surface roughness objectives that are of specific relevance to AM.

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**Figure 4.6** Surface roughness $R_a$ versus the specimen inclination angle $\phi$ for the upper and lower surfaces with directions $\alpha$ and $\beta$ (Fig. 4.4).

**Table 4.3** Linear, exponential, power, and logarithmic curve fit options and associated correlation coefficients ($R^2$) for upper and lower surfaces shown in Fig. 4.6

<table>
<thead>
<tr>
<th></th>
<th>Linear</th>
<th>Exponential</th>
<th>Power</th>
<th>Logarithmic$^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper surface</td>
<td>0.167</td>
<td>0.117</td>
<td>0.234</td>
<td>0.318</td>
</tr>
<tr>
<td>Lower surface</td>
<td>0.318</td>
<td>0.350</td>
<td>0.372</td>
<td>0.425</td>
</tr>
</tbody>
</table>

$^a$Logarithmic provides the highest correlation coefficient for both the upper and lower scenarios.

By accommodating these observations of surface roughness versus surface inclination and by rotating the intended component according to the spatial rotations shown in Fig. 4.7, the associated surface finish can be optimised for the specific design objectives.

**4.3.2 Roughness objectives**

To achieve robust surface roughness outcomes in AM, it is critically important to apply a surface roughness objective that is appropriate for the intended functional and aesthetic objectives. In addition to the area-weighted average roughness, $R_{a_{ave}}$, that is reported in the literature, this section presents a series of novel surface roughness objectives that are of specific relevance to AM.
4.3.2.1 Average roughness

Average roughness, $R_{a\_ave}$, refers to the area-weighted average roughness of each facet within the component geometry (Eq. (4.2)). The area, $A$, associated with each facet may be assessed by the Cartesian coordinates of the associated vertices (Eq. (4.3)) or by Heron’s rule with reference to the facet side lengths ($a$, $b$, and $c$) (Eq. (4.4)).

$$R_{a\_ave} = \frac{\sum_{i=1}^{n} R_{a,i}(\varnothing)A}{\sum_{i=1}^{n} A} \quad (4.2)$$

$$A = \frac{1}{2}|x_1y_2 - x_1y_3 + x_2y_3 - x_2y_1 + x_3y_1 - x_3y_2| \quad (4.3)$$

$$A = \sqrt{1/16[(a + b + c)(-a + b + c)(a - b + c)(a + b - c)]} \quad (4.4)$$

The literature associated with the surface roughness of AM specimens universally reports $R_{a\_ave}$ as the objective function (for example, Refs. [9,10,14,15,29]). Although the average roughness is useful in determining the quality of a manufactured component in terms of roughness, it is not the only parameter of relevance. This work extends the available literature associated with surface roughness by accommodating additional roughness objectives, including peak roughness avoidance, the roughness of relevant surfaces only and weighted average roughness.

4.3.2.2 Peak roughness avoidance

Peak roughness avoidance, $R_{a\_pa}$, returns $\infty$ when the orientation results in any facet roughness value that exceeds the reference limit, $R_{a\_limit}$, and thereby identifies
orientations (if they exist) that avoid the inclusion of excessive roughness (Eq. (4.5)). \( R_{a,pa} \) is useful to avoid roughness types that violate some fundamental design constraint. For example, \( R_{a,pa} \) may be used to identify orientations that do not require supporting structures by setting \( R_{a,limit} \) to the minimum self-supporting build angle (Fig. 4.5).

\[
R_{a,pa} = \begin{cases} \infty, & \text{for } \max(R_{a,i})^n_{i=1} > R_{a,limit} \\ R_{a,ave}, & \text{otherwise} \end{cases} \tag{4.5}
\]

### 4.3.2.3 Roughness of relevant surfaces

The roughness of relevant surfaces, \( R_{a,r} \), is dependent only on facets that are relevant \((r_i = 1)\) to the functionality of the intended component. Facets that are functionally or aesthetically irrelevant \((r_i = 0)\) do not contribute to \( R_{a,r} \) (Eq. (4.6)). The roughness of relevant surfaces provides a useful surface roughness objective for scenarios that have geometric tolerances assigned to mating surfaces (Section 4.4.1) or aesthetic restrictions of surface roughness on visible surfaces only. The \( R_{a,r} \) approach is applied in case study 2 to identify orientations that meet the functional requirement for selected surfaces within a prototype cover (Section 4.4.2) and a hydraulic housing (Section 4.4.3).

\[
R_{a,r} = \frac{\sum_{i=1}^{n} r_i R_{a,i}(\bar{O})A_i}{\sum_{i=1}^{n} A_i r_i} \tag{4.6}
\]

### 4.3.2.4 Weighted roughness

Weighted roughness, \( R_{a,w} \), applies a roughness weighting \( \lambda(\phi) \) to the measured surface roughness of each facet to optimise the desired surface roughness distribution in the finished component (Eq. (4.7)).

\[
R_{a,w} = \frac{\sum_{i=1}^{n} \lambda(\bar{O}) R_{a,i}(\bar{O}) A_i}{\sum_{i=1}^{n} A_i} \tag{4.7}
\]

Weighted roughness is a useful roughness objective because it allows the presence of high roughness facets (unlike for \( R_{a,pa} \)), on the condition that their associated surface area is correspondingly low. For example, in response to the roughness profile observed in Fig. 4.6, the hypothetical roughness weighting shown in Fig. 4.8 is applied in Section 4.4.3 to discourage facets that have high roughness or are not robustly self-supporting.

### 4.3.2.5 Weighted roughness of relevant surfaces

Weighted roughness of relevant surfaces, \( R_{a,w,r} \), applies a roughness weighting \( \lambda(\phi) \) to the measured surface roughness of each facet to promote the desired surface roughness distribution in the finished component (Eq. (4.8)). As for \( R_{a,r} \), facets are defined as either relevant \((r_i = 1)\) or irrelevant \((r_i = 0)\) to the associated surface roughness.
objective. The $R_{a_{w\_r}}$ approach is applied in case study 2 to identify orientations that avoid high roughness values for relevant surfaces (Section 4.4.2).

$$R_{a_{w\_r}} = \frac{\sum_{i=1}^{n} r_i \lambda(\phi) R_a(\phi) A_i}{\sum_{i=1}^{n} A_i r_i}$$  \hspace{1cm} (4.8)$$

4.4 Case studies

Case studies are presented for a surgical implant, a low-volume prototype cover, and a functional hydraulic housing. These case studies demonstrate the enhanced design outcomes that are achievable by the material data and surface roughness objectives developed in this research.

4.4.1 Case study 1: surgical implant design

AM provides significant application in the manufacture of high-value, patient-specific surgical implants [28,30]. Surgical implants have both surgical and biological requirements for specific surface roughness targets. For example, the proposed surgical implant is to be fastened with a surgical-grade screw of predetermined geometry at a vector defined a priori by the surgical team. Based on these inputs, corresponding screw clearance envelopes are specified geometrically (Fig. 4.9). It is highly desirable that the implant surface roughness be determined versus orientation within the build volume such that orientations that avoid high roughness values are avoided, and that screw clearance envelopes be self-supporting such that no post-processing
operation is required to remove internal support material. These orientation maps (Fig. 4.10) allow the identification of optimal implant orientation to meet surgical requirements; however, it is apparent that the identification of global optima requires analysis with a relatively small orientation angle increment, \( \Delta \alpha \).

### 4.4.2 Case study 2: low-volume prototype cover

A low-volume prototype cover is to be manufactured for an automotive concept vehicle (Fig. 4.2). Minimisation of average surface roughness, \( R_{a,\text{ave}} \), is a useful roughness objective; however, it does not fully represent the requirements of this application. In particular, it is necessary to accommodate aesthetic and post-processing roughness requirements:

- The prototype housing is an interior product with visible ‘A-class’ surfaces that are critical to customer perception. Surfaces that are not visible to the customer are not relevant in terms of

![Figure 4.9](image-url) Rear, side and isometric views of the proximal femur, including the zone identified for patient-specific Ti64 additive manufacturing (AM) implant and associated screw clearance envelopes (×4). *CT*, computed tomography.
Surface roughness optimisation for selective laser melting (SLM)

Surface roughness and are defined as ‘B-class’ surfaces. To meet this roughness requirement, B-class surfaces are not included in the surface roughness analysis (Fig. 4.2). The associated roughness of relevant surfaces, $R_{a,r}$, of the prototype component is presented in Fig. 4.11 (left).

- It is necessary to avoid high roughness values that occur as a result of low inclination angles and geometry that is not self-supporting. To meet this roughness objective, a custom roughness weighting was developed (Fig. 4.8). Weighted roughness of relevant surfaces, $R_{a,w,r}$, is presented for the prototype component in Fig. 4.11 (right).

Figure 4.10 Orientation maps of weighted roughness, $R_{a,w}$, of selective laser melting titanium implant versus orientation for $\Delta \alpha = 90, 60, 30, 15, \text{and} 5 \, \text{degrees. Note that local optima are not identified until the number of orientations (and associated computational time) is increased.}$
The orientation map of $R_a_r$ and $R_{a_w_r}$ provides design guidance on the effect of component orientation on the surface roughness objective. The orientation map clearly identifies global minima and maxima and enables an informed trade-off when compromising between competing objectives such as build time and support material consumption. It is apparent that the minima for both $R_a_r$ ($\alpha_1 = 170$ degrees, $\alpha_2 = 0$ degree) and $R_{a_w_r}$ ($\alpha_1 = 160$ degrees, $\alpha_2 = 0$ degree) occur at slightly different locations, indicating that the $R_{a_w_r}$ successfully identifies a more favourable orientation for the design objectives.

Figure 4.11 Orientation map of weighted average roughness, $R_{a_w}$ (left), and weighted roughness of relevant surfaces, $R_{a_w_r}$ (right), for all facets of the prototype housing (Section 4.4.2) for $\Delta\alpha = 30, 15,$ and 5 degrees.

The orientation map of $R_a_r$ and $R_{a_w_r}$ provides design guidance on the effect of component orientation on the surface roughness objective. The orientation map clearly identifies global minima and maxima and enables an informed trade-off when compromising between competing objectives such as build time and support material consumption. It is apparent that the minima for both $R_a_r$ ($\alpha_1 = 170$ degrees, $\alpha_2 = 0$ degree) and $R_{a_w_r}$ ($\alpha_1 = 160$ degrees, $\alpha_2 = 0$ degree) occur at slightly different locations, indicating that the $R_{a_w_r}$ successfully identifies a more favourable orientation for the design objectives.
4.4.3 Case study 3: functional hydraulic housing for an engineering application

The hydraulic housing shown in Fig. 4.13 is to be manufactured by SLM for low- to medium-volume production. For this functional engineering application, there are no aesthetic requirements for surface finish. However, it is technically necessary that the surface finish of the mating features and mounting holes be minimised to ensure robust technical function.

**Figure 4.12** Cover component orientation for minimum weighted roughness, $R_{a_w}$ (left). For comparison, the orientation for the maximum $R_{a_w,r}$ is included (right). Note the difference in scale.

**Figure 4.13** Functional housing for an engineering application, indicating mounting holes ($\times 4$) and features ($\times 4$) that contribute to the surface roughness objective.
For this scenario, the average surface roughness, $R_{a\_ave}$, is not an appropriate surface roughness objective because the surface roughness of features other than the mating features is inconsequential to component function. For example, minimising average surface roughness of the entire component results in a minima of $R_{a\_ave}$ at $\alpha_1 = \alpha_2 = 0$ degrees (Fig. 4.14). This minima repeats with a period of 180 degrees and results in low $R_a$ facets on the large planar surfaces and mounting holes (however with large $R_a$ facets on cylindrical mounting holes). However, when only relevant surfaces are considered, the global minima for $R_{a\_r}$ occurs at $\alpha_1 = 90$ degrees and $\alpha_2 = 0$ degree (ie, the minima orientation for $R_{a\_ave}$ does not exist), and low $R_a$ facets occur on the cylindrical mating features (Fig. 4.12, lower). Note that for the orientation that is optimal for minimising average surface roughness over the entire component ($\alpha_1 = \alpha_2 = 0$ degree; Fig. 4.14, top), the $R_{a\_ave}$ of relevant facets only is not optimal

Figure 4.14 Average surface roughness, $R_{a\_ave}$, and facet $R_a$ at min ($R_{a\_ave}$) for functional housing: all surfaces (upper), relevant surfaces only (lower). $\Delta \alpha = 2$ degree.
This case study demonstrates that the use of $R_{a\text{-ave}}$ as the surface roughness objective can result in erroneous design guidance when the component consists of surfaces that are irrelevant to component function.

### 4.5 Conclusions

To provide greater insight into the optimal component orientation for AM, this work contributes various outcomes to the available literature:

- To ensure robust design data, the surface roughness versus build inclination of SLM-manufactured Ti64 was assessed experimentally and reported in detail, including measured roughness data and high-resolution macroscopy for upper and lower surfaces. Based on these data, correlations between the orientation and the observed surface roughness are presented, including the dominance of staircase effects and adhered particles on observed roughness when inclination tends towards horizontal ($\phi \to 0$ degree) and vertical ($\phi \to 90$ degrees), respectively.

- Manufactured products typically include surfaces that are not relevant to customer satisfaction or function. For example, consumer products consist of visible and hidden surfaces, and engineered components have critical roughness tolerances associated with key surfaces. The methods proposed in this research enable the discrimination of relevant and irrelevant surfaces when assessing the associated surface roughness objective. It was shown that this method can avoid erroneous design guidance when the component consists of surfaces that are irrelevant to component function.

- The available literature considers only the minimisation of average surface roughness. This work proposes novel surface roughness objectives, including penalty avoidance and penalty weighting, to avoid specific roughness types. When applied to optimise the orientation of a low-volume prototype cover, the proposed penalty-weighting method identified a more favourable orientation than optimisation methods based on average surface roughness only.

- An infinite number of component orientations exist. The orientation maps presented in this work clearly identify global minima and associated trends, enabling an informed trade-off when compromising between competing objectives such as build time and support material consumption.

### Nomenclature

<table>
<thead>
<tr>
<th>$\alpha_1$ (degrees)</th>
<th>Rotation angle about the $X_0$ axis between ${X_0, Y_0, Z_0}$ and ${X_1, Y_1, Z_1}$</th>
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</thead>
<tbody>
<tr>
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<tr>
<td>$\Delta\alpha$ (degrees)</td>
<td>Orientation angle increment</td>
</tr>
<tr>
<td>$\phi$ (degrees)</td>
<td>Filament inclination angle</td>
</tr>
<tr>
<td>$i$ —</td>
<td>Facet index</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
</tr>
<tr>
<td>( n )</td>
<td>Number of facets within a component</td>
</tr>
<tr>
<td>( A )</td>
<td>Facet area (m²)</td>
</tr>
<tr>
<td>( R_{a,i} )</td>
<td>Average roughness of facet ( i ) (μm)</td>
</tr>
<tr>
<td>( R_{a,ave} )</td>
<td>Area-average roughness (μm)</td>
</tr>
<tr>
<td>( R_{a,pa} )</td>
<td>Peak avoidance surface roughness (μm)</td>
</tr>
<tr>
<td>( R_{a,limit} )</td>
<td>Maximum allowable ( R_a ) value for peak avoidance (μm)</td>
</tr>
<tr>
<td>( R_{a,r} )</td>
<td>Surface roughness accommodating relevant surfaces (μm)</td>
</tr>
<tr>
<td>( R_{a,w} )</td>
<td>Weighted surface roughness (μm)</td>
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<td>( R_{a,w,r} )</td>
<td>Weighted surface roughness accommodating relevant surfaces (μm)</td>
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</tr>
<tr>
<td>( l )</td>
<td>Overhang distance (m)</td>
</tr>
<tr>
<td>( y_j )</td>
<td>Vertical distance from the mean line to the data point (m)</td>
</tr>
<tr>
<td>( N_{orient} )</td>
<td>Number of assessed orientations (—)</td>
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<tr>
<td>( p )</td>
<td>Unit vector oriented vertically downwards to the platen (—)</td>
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### References


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