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Surface texture measurement for additive manufacturing

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Abstract

The surface texture of additively manufactured metallic surfaces made by powder bed methods is affected by a number of factors, including the powder’s particle size distribution, the effect of the heat source, the thickness of the printed layers, the angle of the surface relative to the horizontal build bed and the effect of any post processing/finishing. The aim of the research reported here is to understand the way these surfaces should be measured in order to characterise them. In published research to date, the surface texture is generally reported as an Ra value, measured across the lay. The appropriateness of this method for such surfaces is investigated here. A preliminary investigation was carried out on two additive manufacturing processes—selective laser melting (SLM) and electron beam melting (EBM)—focusing on the effect of build angle and post processing. The surfaces were measured using both tactile and optical methods and a range of profile and areal parameters were reported. Test coupons were manufactured at four angles relative to the horizontal plane of the powder bed using both SLM and EBM. The effect of lay—caused by the layered nature of the manufacturing process—was investigated, as was the required sample area for optical measurements. The surfaces were also measured before and after grit blasting.

Introduction

Additive manufacturing (AM) of metals has great potential as a manufacturing process; however, an area of uncertainty for potential adopters is that of the surface texture. Metal AM parts have an unusual and variable surface texture which is not comparable to conventionally-manufactured surfaces. The objective of this work was to understand the characteristics of an AM surface and then to propose an appropriate tactile or optical method for measuring it—in particular with respect to the lay—and if possible to suggest some appropriate measurement parameters from the list of available profile and areal parameters. Two widely used metal powder bed processes were considered, selective laser melting (SLM) and electron beam melting (EBM) as their surfaces have similar features due to the similarity of the process physics.

Characterisation of an AM surface

AM processes are additive in the sense that they add material to create part geometry, rather than removing material as is the case with subtractive processes such as milling or turning. The addition of material occurs sequentially in a series of flat layers, resulting in a part which has a stepped surface, as shown in figure 1. As the local slope of the surface changes, so does the frequency of the steps. In this paper, the local slope is measured by inclination of the surface from the horizontal plane as the part was built: a horizontal surface has a slope of 0° and a vertical surface has a slope of 90°.

If each layer was built perfectly, as in figure 1, the surface texture would be a trigonometric function of the stepped geometry. However, the layers become deformed during the build process. Each layer is created by melting selected areas of a powder layer. The powder consolidates and melds with the layer below,
as shown in figure 2. Certain conditions in the melt pool can induce ‘balling’ of the molten material (Strano et al 2012), which can then disrupt the edge of the melt pool, affecting the shape of the layer edge. Gravity also affects melt pools that are created on unsupported layers, which sag into the un-melted powder below, resulting in a much rougher surface on the underside of the component (referred to as the ‘downskin’) than on the upward facing surfaces (referred to as the ‘upskin’). This differential roughness effect is compounded by the unequal heat dissipation rates in powder, compared to the solid material, which create thermal gradients and destabilises the melt pool, further disrupting the shape of the layer edge (Vandenbroucke and Kruth 2006). As the melt pool solidifies, partially melted particles from the surrounding powder also stick to the edge of the layer and this also contributes to the final surface texture.

The net result of the above effects is a surface with a multi-directional particulate texture that has an underlying directionality (‘lay’) and that also varies around the component, as the local surface slope changes. An example AM surface is shown in figure 3 and a representative image of the powder that created the surface is shown in figure 4.

Models for predicting AM surface texture have been proposed, for example Daekeon et al (2009) and Pérez et al (2001), both give equations to model the stepping effect. Strano et al (2012) adds the effect of edge powder particles and—despite not modelling the heat and gravity related influences—provides a good match with experimental data. Karlsson et al (2013) studied the effect of different particle sizes and building layer thicknesses in the EBM process. They found that smaller particle sizes increase the amount of particles stuck to the surface.

Very little research was found on the characterisation of AM surfaces. Correspondence with several metal powder bed AM machine manufacturers (EOS, Renishaw and Concept Laser) indicated that they characterise their AM component surfaces primarily by tactile profile (stylus) measurement methods using Ra and Rz parameters, and their measurements are taken across the lay and in accordance with ISO 4287 (1997), ISO 4288 (1996). The researchers in the literature cited here also characterised surfaces by a tactile profile measurement along the surface of the part, generally recording Ra or Rz. Little reference was found to other parameters, or areal measurements, either with tactile or optical instruments.

**Method**

Based on the literature review, the process variables shown in table 1 were identified. There are also several secondary factors which have been observed anecdotally to have some influence on surface texture. Their description and experimental values are given in table 2. These factors were not varied during the experimental work, however they are included for completeness.

**Coupon design**

Measurement test coupons were designed to vary the slope parameter and allow use of tactile and optical measurements, as shown in figure 5. The design took into account the following requirements:

- Common design for SLM and EBM process.
- No curved surfaces (to minimise the experiment variables).
- Clear line-of-sight for optical methods.
- Access for the probes with contact methods.
- Ability to measure along and across the lay.
- A minimum measurable surface area of 20 × 20 mm.
- Ability to mount for grit blasting.
- Coupon thickness: thin enough to fit on measurement instrumentation, thick enough to not warp during build or break during post-processing.

The coupons were built by SLM and by EBM in Ti6Al4V. Their position in the build chamber for both builds is shown in figure 6. The thin coupons were used for the destructive tests. Two extra 60° coupons were built at different positions in the build chamber, however a comparison of the variation of their surface textures was inconclusive and is not reported in this work.

When evaluating the surface of AM parts, there is an additional consideration—the external supports that are built at the same time as the part, as for example are visible on the 0° and 30° coupons in figure 6. The thin coupons were built at different positions in the build chamber, as for example are visible on the 0° and 30° coupons in figure 6. Supports are used in both EBM and SLM builds, albeit for different reasons (Gibson et al 2010) and their
Figure 2. Powder around build in the powder bed process.

Figure 3. SEM plan view of a flat surface built by SLM and EBM at a slope of 30°.

Figure 4. SEM image of powder for SLM (left) and EBM (right).
removal post-build can leave witness marks that interfere with the surface texture measurement. For this reason, some measurements could not be taken on some of the coupons’ downskins.

**Characterisation methods**

The coupons’ surface texture was measured, on both the upskin and downskin, using three measurement techniques:

- Tactile profile measurements.
- Optical areal measurements.
- Proprietary image analysis with a simulated tactile probe tip on images of coupons that had been sectioned across the lay.

The instruments used and their description are given in table 3.

The Ra parameter was used for the tactile profile measurements and they were repeated three times at each position on each face of the coupons. The cut-off length was set to 8 mm, in accordance with ISO 4288.

Optical areal measurements were made at three different positions on each face of the coupons. The area of the measured topography was chosen to be nominally 8 mm by 8 mm to match the size of the cut-off wavelength that corresponded to the Ra values representative for the measurement results found with the tactile profile method. The S-filter nesting index was limited by the lateral resolution of the instrument and set at 8 μm. The L-filter nesting index was established using an area scale analysis method, which calculates the surface area of the measured topography as a function of scale (Brown 2013). Sa and Sq were evaluated initially and then several other areal parameters were considered to evaluate whether they could be used to describe the observed variations in surface texture.

The destructive measurement required the samples to be cut, embedded, ground and polished as per the preparation for a typical microstructure analysis. The sectioned surfaces were imaged using an Alicona IFM at 5x magnification and the images were stitched together with the Alicona software. Finally Matlab was used to calculate an Ra equivalent value, using the resolution/pixel size of the image as a reference.

**Results and discussion**

**Profile measurements**

Profile measurements were undertaken on the EBM coupons. The 0° and 30° coupon downskins could not be measured because of the supports used during the build. With the exception of the 0° coupon upskin, the range of values obtained from the along- and across-the-lay measurements overlap each other, as shown in figure 7. For the 0° coupon upskin, the difference between the minimum across-the-lay and maximum along-the-lay Ra was 2.9 μm. The overlap of the curves for the downskin measurements indicates there is no clear distinction between the values that are obtained along and across the lay. Therefore, for EBM coupons, the direction of measurement with respect to the lay for non-horizontal surfaces can be considered insignificant.

For the SLM coupons, the spread of results was much narrower and some measurements did not overlap, as shown in figure 8. Of those which did not overlap, the 0° downskin showed the largest deviation and difference in average Ra between along- and across-the-lay (4.8 μm). This is most likely due to the effect of the support removal operation which can leave traces of supports on the surface, affecting the surface texture. The other results overlap, and as with the EBM results, this indicates that there is no clear distinction between the values that are obtained along and across the lay.

**Destructive profile measurements**

Test coupons with a 30° and a 60° slope were sectioned and simulated Ra measurements were performed.

The results were similar to the tactile profile measurement results, though a direct comparison with tactile measurement results is not meaningful. A secondary—but significant—result of the imaging analysis is that re-entrant features were observed on
the coupon surfaces, an example of which is shown in figure 9. These features are not captured by stylus or optical measurements.

Areal measurements
Optical areal measurement of the coupons indicated that a 2.5 mm by 2.5 mm evaluation area is sufficient

Figure 5. Coupon geometry showing a range of profile trace directions with respect to lay and the built slope of the coupons relative to the chamber platform.

Figure 6. Perspective view of coupons on EBM build plate.

Table 2. Other factors affecting surface texture.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Description</th>
<th>Experimental value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Powder reuse</td>
<td>The number of times the powder has been recycled is known to affect part quality</td>
<td>Only one build was completed for this work using a recycled powder</td>
</tr>
<tr>
<td>Variation from AM one machine to another</td>
<td>Anecdotal evidence suggests that variation occurs between individual machines of the same make and model</td>
<td>Only one build was completed for this work</td>
</tr>
<tr>
<td>Position on build platform</td>
<td>Anecdotal evidence suggests the position of the part on the build platform can affect part quality</td>
<td>No multiple position results are reported in this work</td>
</tr>
<tr>
<td>Recoater blade</td>
<td>It has also been suggested that the orientation of the parts to the recoater blade, which spreads each layer of powder during the build, can also affect surface texture</td>
<td>All test coupons were positioned parallel to the recoater blade</td>
</tr>
<tr>
<td>'Cake’ removal</td>
<td>The EBM process results in the parts being created in a partially sintered ‘cake’ of powder which must be removed manually and can cause variations in the surface texture of the finished part</td>
<td>An experienced operator limited variations as much as possible</td>
</tr>
<tr>
<td>Post processing</td>
<td>AM parts are usually post-processed to improve the surface texture</td>
<td>The coupons were grit blasted using pink alumide, and measured both before and after the grit blasting</td>
</tr>
</tbody>
</table>
to capture the significant characteristics of the AM surfaces measured in this work. This conclusion was drawn from a representative area scale analysis of the SLM and EBM surfaces in the experiment. An example of such measurements is shown in figure 10. The complexity of the sample (average gradient over a decade of the relative area (Brown 2013)) indicates that the spatial wavelength of interest is below 2.5 mm,
which in figure 10 corresponds to the region on the right-hand side of the peak where the curve plateaus (approximately $3 \times 10^6 \, \mu m^2$ on the $x$-axis). Therefore, there is no need for an L-filter nesting index larger than 2.5 mm. The position of the peak is an indication of a major change in the relative area between two successive tile sizes. As can be seen in figure 10, this conclusion also applies to the grit blasted coupons. Note that at this level of $Ra$, ISO 4288 would recommend an evaluation length of 8 mm.

**Other parameters**

Without any functional specifications and with only a loose requirement for calculating $Sa$, the selection of relevant areal parameters was difficult. The Ssk parameters showed potential for differentiating between the upskin and downskin of the SLM coupons at 60°, both as-built and grit-blasted (see figure 11), whereas the $Sa$ parameter could only differentiate the upskin and downskin of the SLM coupons after grit-blasting.

At this stage, no other areal surface texture parameters were found to be capable of clearly differentiating between surfaces. Further recommendation of preferred measurement parameters would depend on the intended function of the surface, as is the case with surfaces manufactured conventionally.

There was initial uncertainty as to whether optical measurement methods are suitable for AM surfaces. The surfaces’ reflective material and particulate characteristics could have been expected to cause problems with reflected light-based measuring instruments. During the experimental work, no optical artefacts were observed which would preclude the use of optical measurement methods for such surfaces. The only limitation encountered was the as-built SLM 0° upskin, for which the optical measurement failed. The 0° upskin is the most reflective surface slope which

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**Figure 9.** As-built EBM 60° slope section images.

**Figure 10.** Area scale analysis results for EBM as-built coupon produced at 60°: upskin as-built (denoted by ◊), downskin as-built (denoted by □), upskin post-processed (denoted by ●) and downskin post-processed (denoted by ×).
may have contributed to this. Actual components may not generally have large areas of flat 0° slope surfaces that need characterising, but this result should be kept in mind.

Conclusions

From the measurement results the following conclusions can be made:

- There was no clear distinction between the tactile profile measurement results along and across the lay, for EBM or SLM coupons, so the direction of the profile when measuring these surfaces can be considered to be of little significance.

- When using optical areal measurement methods, a 2.5 mm L-filter nesting index appears sufficient to capture the data required to characterise an AM surface produced by SLM or EBM. This applied to as-built surfaces and surfaces blasted with pink alumide. It is anticipated that a 2.5 mm cut-off length will also apply to tactile measurements. If this is confirmed, it will mean using an 8 mm cut-off length, as recommended in ISO 4288 (1996), is not necessary.

- Sa and Sq were found to be suitable areal measurement parameters for AM surfaces. In addition, the Ssk parameter differentiates the upskin from the downskin of both as-built and post-processed SLM coupons. Further work would be needed to confirm the usefulness of this parameter for characterisation.

- SLM and EBM surfaces can include re-entrant features that cannot be observed using tactile or optical non-destructive measurement methods. The destructive method described in this article can therefore be used alongside non-destructive methods to provide supplementary data on the features of a surface that is being characterised.

- The surfaces of Ti6Al4V SLM and EBM parts did not cause artefacts with the optical measurement equipment used in this work, but the 0° SLM upskin may be too reflective to give reliable optical readings.

Recommendations for further work

Further evaluation of the 2.5 mm L-filter nesting index and the significance of lay for process variables that were not tested in this project is recommended. For example, the consideration of the minimum slope to which the 2.5 mm² area applies and the effect of different layer thicknesses.

The applicability of a 2.5 mm by 2.5 mm areal measurement window to a 2.5 mm tactile profile measurement trace length needs to be verified.

The extent of re-entrant features should be evaluated over the whole range of surface slopes from 0 to 360°, as well as the effect of other process variables such as material or layer thickness. This would then inform quality control decisions on the inspection of AM parts.

In the long term—since the surface’s function determines what features should be measured and by implication the most suitable parameters to use—an industrial survey asking potential end users for their predicted AM surface functions could guide further research into AM surface characterisation.

Acknowledgments

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