Surface Topography: Metrology and Properties

Surface-specific additive manufacturing test artefacts

Andrew Townsend©, Radu Racasan and Liam Blunt
The Future Metrology Hub, University of Huddersfield, Huddersfield HD1 3DH, United Kingdom
E-mail: a.townsend@hud.ac.uk

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Abstract

Many test artefact designs have been proposed for use with additive manufacturing (AM) systems. These test artefacts have primarily been designed for the evaluation of AM form and dimensional performance. A series of surface-specific measurement test artefacts designed for use in the verification of AM manufacturing processes are proposed here. Surface-specific test artefacts can be made more compact because they do not require the large dimensions needed for accurate dimensional and form measurements. The series of three test artefacts are designed to provide comprehensive information pertaining to the manufactured surface. Measurement possibilities include deviation analysis, surface texture parameter data generation, sub-surface analysis, layer step analysis and build resolution comparison. The test artefacts are designed to provide easy access for measurement using conventional surface measurement techniques, for example, focus variation microscopy, stylus profilometry, confocal microscopy and scanning electron microscopy. Additionally, the test artefacts may be simply visually inspected as a comparative tool, giving a fast indication of process variation between builds. The three test artefacts are small enough to be included in every build and include built-in manufacturing traceability information, making them a convenient physical record of the build.

1. Introduction

Metal additively manufactured (AM) components, made using the powder bed fusion (PBF) process, are now being used in applications where the as-built surface is functional and critical, such as medical and dental implants [1, 2] and electromagnetic horn antennae [3]. For those components where the as-built surface is machined (to create sealing surfaces for example) the as-built surface may give an indication of the internal structure, for example, the likelihood of internal porosity; however, at the time of writing the authors have found no references verifying the link between surface texture and porosity. The extremely complex AM build process presents quality-based challenges for initial configuration and for continued process control. Once benchmarked, surface changes during successive builds may give an indication of potential problems, both with the functional surface and with the internal structure. AM surfaces are complex, with local asperities, partially melted powder and repeating features created by the laser or electron beam scan strategy and by the build layering [4]. Metrological techniques that have been employed to provide quantitative and qualitative information from AM surfaces include contact stylus [5, 6], focus variation microscopy [7, 8], confocal microscopy [9, 10] and scanning electron microscopy [11, 12]; these techniques have been compared and contrasted in [4]. Recent work has been performed on the extraction of surface texture data using X-ray computed tomography (CT) [7], with subsequent work performed to investigate factors influencing the system accuracy and configuration optimisation [13–15]. All these metrological methods have different measurement constraints and specific maximum limits on artefact size and configuration for ease and accuracy of measurement. The artefact set reported here was designed considering these constraints. There have been several AM artefacts designed for analysis of dimensional and form accuracy [16–21]. These artefacts, by necessity, tend to be large and so occupy a large volume in the build chamber and are costly in time and materials. Some artefacts, such as that proposed by Moylan [21] include sections designed for surface measurements. An artefact suite, proposed by the ASTM F42/ISO TC 261 Joint Group (JG) for standard test artefacts (STAR) includes user-selectable,
application-specific artefacts. This suite includes a series of platens to be built at a range of angles to the build plate to investigate the surface changes as the build angle is varied [22]. A similar concept was used by Triantaphyllou to evaluate selective laser melting (SLM) and electron beam melting (EBM) AM surfaces built at different angles to the horizontal [5]. A more complex faceted sphere, with a range of surface plane angles, was used by Grimm for surface characterisation [10]. The additive manufacturing surface artefacts (AMSA) series of three artefacts proposed here are intended to be used individually or as a group, depending upon the specific application. They are designed to provide more information than can be provided by a simple planar surface. The artefacts may be used for deviation analysis when scanned using fringe projection, interferometry or using CT and then compared to the CAD model. Sub-surface analysis may be performed by milling a series of varying height bosses to expose material seven successive build layers below the surface. A 1:25 gradient slope is included for layer edge analysis. The artefacts include ISO 25178-70 Type ASG star-shaped grooves [23] and decreasing-wavelength sine waves for the analysis of the limits of build resolution. The artefacts may be incorporated into each build and a simple visual inspection of the artefact may be performed, comparing the sample to a reference a sample, similar to the use of visual surface inspection plates, such as those provided by Rubert [24]. The three AMSA artefacts are configurable to a particular build chamber, powder and component function. All three artefacts have built-in manufacturing traceability (part number, revision, serial number, material, layer thickness). The exterior wall of all artefacts is a minimum of 0.5 mm above the critical surfaces to reduce the probability of accidental damage, but still permit measurement access. The artefacts will fit within a 30 mm diameter cylinder with a height of 10 mm, allowing the artefact to be measured on most inspection machines, include scanning electron microscopes (SEM). The small size means there will be, compared to the larger dimension-
based artefacts, lower material costs, reduced build time and reduced chamber utilisation.

2. Methodology

Sample AMSA series parts were built using two PBF AM machines. One set of artefacts were manufactured using an Arcam Q10 EBM machine. The EBM raw material was Ti6Al4V ELI, with a nominal powder particle size of 45–100 \(\mu m\). The AMSA artefacts were built with the measurement surfaces orientated both horizontally and vertically. The EBM test build included the AMSA series of artefacts, together with nine bars and two multi-faceted hemi-spheres (similar in concept to the faceted sphere used by Grimm). The hemi-spheres were included to evaluate the surface texture variation at different build angles. The bars were included to evaluate surface texture variation within the build volume. The positions of the AMSA artefacts within the build is shown in figure 1.

A second set of AMSA series artefacts were manufactured using a Renishaw AM250 SLM machine. The raw material was also Ti6Al4V ELI, with a nominal powder particle size of 15–45 \(\mu m\). All SLM artefacts were built with the designed measurement surfaces orientated horizontally.

2.1. AMSA1 artefact

AMSA1 includes three measurement areas, see figure 2: the first is a flat area parallel to the artefact base, designed for areal surface measurement and characterisation (for example per ISO 25178-2 [25]) or profile characterisation (for example per ISO 4287 [26]). The second area includes a 1:25 gradient plane. This area is designed to allow examination of the build-layer transition edge. This slope was included by Moylan in the 2012 NIST artefact [21]. The third area on the artefact is a series of ten round bosses, each with a diameter of 2.5 mm, but of different heights. The height difference between successive bosses is equivalent to the build-layer thickness. This will produce the minimum difference between successive boss heights. If the bosses are milled to the height of the artefact edge wall surfaces then between one and seven layers below the as-built surface will be exposed. The surfaces can be examined for porosity or, after suitable etching and polishing, metallographic inspection of each surface may be performed. Two of the bosses have as-built surfaces below the edge wall. The heights of these (un-machined) bosses allow calculation of the actual material machined
from the higher bosses (especially if the wall is accidentally machined). Prior to manufacture the build-layer thickness is entered into the CAD design. The physical height of all bosses is generated automatically and the build-layer height is printed on the side of the artefact, reducing the possibility of operator error.

2.2. AMSA3 artefact
Artefact AMSA3 includes ISO 25178-70 Type ASG star-shaped grooves on the top surface, see figure 3. This areal material measure, as with all material measures presented in ISO 25178-70, has been specifically designed for the assessment and correction of systematic errors [23]. Type ASG star-shaped grooves have been used previously in AM research [27]. The spokes of the star become indistinguishable at some radial distance from the centre when the lateral resolution limit is reached. Artefact AMSA3 includes a wedge section with concentric rings to aid in visual location of the resolution limit. A series of three AMSA3 artefacts were included in the EBM build, each with a different spoke width and spacing (for identification purposes: coarse, medium and fine). This was done to assess the correct spacing for this build configuration. A single, optimised, AMSA3 artefact would be included in subsequent builds.

Table 2. AMSA1 EBM artefact surface filtering per ISO 25178-3.

| Sample       | L-filter per ISO 25178-3 (mm) | S-filter per ISO 25178-3 (mm) |
|--------------|-------------------------------|-------------------------------|
| EBM horizontal | 3.5                           | 0.020                         |
| EBM vertical   | 3.5                           | 0.020                         |

Table 3. AMSA1 EBM artefact parameter data per ISO 25178-2.

| Sample       | Sa/μm | Sz/μm | Sal/mm | Str   |
|--------------|-------|-------|--------|-------|
| EBM horizontal | 8.9   | 73.7  | 0.33   | 0.49  |
| EBM vertical   | 32.2  | 274.8 | 0.09   | 0.78  |
2.3. AMSA4 artefact

AMSA4 includes three sections, each with a constant amplitude, decreasing-wavelength structured sine wave, see figure 4. The equations for the three sections are given in equation (1) (amplitude 800 µm pk-pk), equation (2) (amplitude 400 µm pk-pk) and equation (3) (amplitude 200 µm pk-pk).

\[ Y = \frac{\sin \left( \frac{2}{5} X^2 \right)}{2.5} \text{ mm} \]  
\[ Y = \frac{\sin \left( \frac{2}{5} X^2 \right)}{5} \text{ mm} \]  
\[ Y = \frac{\sin (X^2)}{10} \text{ mm.} \]

This artefact is designed to give a visual indication of the resolution limit and the build-deviation when compared to the CAD model.

3. EBM artefact results

3.1. AMSA1

Figure 5 shows a deviation analysis performed between a CT scan of the EBM AMSA1 artefact and the CAD model. The measurement settings for the Nikon XT H 225 CT are shown in table 1.

The scale-bars shown on all deviation analysis figures are scale-thresholded from 0.5 mm extra material (blue) to 0.5 mm missing material (red). This thresholding permits comparison of the deviations for each artefact, as similar deviations will be displayed with the same colour. All deviations above 0.5 mm from the nominal are shown with the same colour. The horizontally-built artefact, figure 5(a), shows a raised edge around the boss features and along the edges of the flat section. The 1:25 slope section has a raised edge around the outside and at the layer transition areas, with some missing material just before the transition to the next higher layer. This is due to a combination of layer thickness and model slicing. The vertically-oriented artefact, figure 5(b), shows clear missing material at the bottom of the cylindrical bosses, with a deviation in excess of 0.5 mm. The surface here was unsupported in the build.

Figure 6 shows the horizontally and vertically-built surfaces of the AMSA1 artefact. SEM micrographs of areas from the flat section, the 1:25 gradient slope and one boss are shown for each build orientation. The diagonal build strategy can clearly be seen in the horizontal flat surface. The layer-to-layer strategy change can be seen in the 1:25 gradient slope micrograph. The flat surface section of the horizontally and vertically-built EBM artefacts were measured using an Alicona G4 focus variation instrument with a 10× objective lens installed. Lateral sampling distance was 2.33 µm, with a vertical resolution of 0.5 µm.

It should be noted that the area of the horizontal EBM sample suitable for measurement was limited by the raised edge of the flat section, see the false-colour height map, figure 7. Least-squares levelling and filtering per ISO 25178-3 was applied to the data from both samples, see table 2.

Amplitude and spatial parameters generated from the levelled and filtered surface data are given in table 3. False-colour height maps of the evaluated areas of the levelled and filtered horizontally and vertically-built surfaces are shown in figures 8 and 9 respectively.

The melt pool, created on the horizontal surface, produces a significantly smoother surface than the build side surface. The average roughness, Sa, and the maximum peak-to-valley height, Sz, are both significantly greater for the vertically-built side surface, see table 3. However, these amplitude parameters do not fully characterise the surface. ISO 25178-2 spatial parameter values may be generated from the data to provide additional information about the surface and the manufacturing process itself. The parameters Sa,

![False-colour height map of the levelled and filtered vertically-built EBM surface.](image)
the fastest decay auto-correlation length and \( \text{Str} \), the texture aspect ratio, relate to the spatial properties of the surface and are useful for differentiating between and characterising highly textured (deterministic) and random (stochastic) surfaces [28]. A large value of \( \text{Sal} \) indicates that the surface is dominated by longer wavelength components. The value of \( \text{Sal} \) for the horizontal and vertical surfaces are 0.33 mm and 0.09 mm respectively. The larger-scale repeating features on the horizontally-built surface produced by the electron beam scan strategy can clearly be seen in figure 8. The value of \( \text{Str} \) can range between 0 and 1, with smaller values indicating a stronger texture directionality or lay. The value of \( \text{Str} \) for the horizontal and vertical surfaces are 0.49 and 0.78 respectively, the lower value of \( \text{Str} \) for the horizontally-built surface indicating a distinct directionality to the surface, again, clearly visible in figure 8.

3.2. AMSA3

Figure 10 shows photographs and CT-CAD deviation analyses of the three EBM AMSA3 artefacts built horizontally and vertically. The differentiation between the spokes of the star-shaped grooves is better for the vertically-built artefacts, see figure 11.

The location where the radial spokes become indistinguishable was, as expected, closest to the centre of the star for the coarse build and furthest from the centre of the star for the fine build for both the horizontally and vertically-built artefacts.

The down-facing surfaces of the vertically-built artefacts exhibit local missing material, see the deviation analyses, figure 10. The width of the outer spoke of the medium star is approximately 1.5 times the width of the horizontally-built spoke at the same location, see figure 12.

3.3. AMSA4

Figure 13 shows the horizontally-built and vertically-built AMSA4 artefact, together with SEM micrographs and CT-CAD deviation analyses. The micrographs show the areas where the decreasing-wavelength sine waves can no longer be resolved. The transition is more distinct for the horizontally-built surface because of the generally smoother surface, however the resolution-limit for both surfaces was approximately at the middle of the fine sine wave section of the artefact. The deviation analysis of the horizontally-built artefact shows the edges with excess material (shown in blue), as seen on artefact AMSA1.

3.4. Artefact base deviation

CT-CAD deviation analyses, showing the underside of AMSA3 and AMSA4 are shown in figure 14. The excess material of the support structures can be seen (blue). Both artefacts also have missing material (red) on the vertical sides adjacent to the underside, due to slumping of the locally unsupported edge of the base.

4. SLM artefact results

4.1. AMSA1

Figure 15 shows the SLM AMSA1 artefact. It can be seen that, generally, the SLM build surface finish is superior to the horizontally-built EBM AMSA1 artefact (figure 6). Build scan direction is less distinct on the surface of the SLM sample and there is less deformation. The surface roughness, \( \text{Sa} \), of the flat surface section of the SLM artefact was 7 \( \mu \text{m} \) after levelling and filtering with an L-filter value of 3.5 mm and an S-filter value of 0.020 mm. The \( \text{Sa} \) value for the EBM horizontal surface was 8.9 \( \mu \text{m} \) (see table 3).
Figure 16 shows the surface of the SLM AMSA3 artefacts. The resolution of the SLM artefact is superior to the fine EBM artefact, which was built with the same spoke width and spacing as the SLM artefact. The radial location at which the spokes become indistinguishable is clearly closer to the centre of the artefact for the SLM build. However, there are two concentric rings within the star where the spokes are enlarged both laterally and vertically, see figure 17.

Figure 17. EBM AMSA artefact, SEM micrographs of the inner spoke area (a) horizontal build, (b) vertical build.

Figure 18 shows the SLM AMSA4 artefacts. The resolution of the SLM artefact is clearly superior.
to the horizontally-built EBM artefact. The peaks of the shortest wavelength section of the artefact manufactured on the SLM system were resolvable.

5. Discussion

There is a clear difference between the vertically-built and the horizontally-built EBM surfaces. The resolution is slightly higher for the horizontal surface, as observed on the Type ASG star-shaped grooves. As expected, the surface characteristics are different, with the horizontal surface similar to the appearance of weld tracks with embedded partially melted raw material particles. The vertically-built surface has a higher proportion of partially melted particles and smaller-scale surface ridges. Unsupported vertical surfaces, such as the side of the bosses of the vertically-built surface have linearly greater than 0.5 mm missing material when compared to the CAD model. This information will influence the amount and location of additional material required to be added prior to the build to assure complete clean-up of any post-processed surface, such as sealing or bearing surfaces. The surface texture information may be used to configure the build orientation of the production components within the chamber. The SLM component had clearly superior resolution and surface texture but there were local build anomalies highlighted by the ISO 25178-70 Type ASG material measure. Analysis of these anomalies may lead to modification of the AM machine build parameters, with further samples made to evaluate the corrective action. The configuration of all the AMSA series artefacts is flexible and may be modified based on the initial results obtained. For example, the SLM surface resolution was sufficiently fine that the smallest decreasing sine wave section of AMSA4 was resolved. The intention of these sine wave sections was to give a visual indication of the resolution limit. The artefact may simply be re-designed to reduce the wavelength of the section. The flat surface of the EBM AMSA1 artefact included as raised edge that reduced the measurement area. The reasons for the raised edge may be investigated and, additionally, if required, the artefact design may be modified to include a wider measurement section. Many machines, such as the Renishaw AM250 SLM machine, allow the selection of build parameters for each part made within one build. This allows experimentation to optimise AM build parameters quickly once a problem is discovered. Future work will also include further investigation of the sensitivity of surface texture parameters to

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**Figure 14.** EBM deviation analysis (a) AMSA3, (b) AMSA4.

**Figure 15.** AMSA1 SLM artefact (horizontal build).

**Figure 16.** AMSA3 SLM artefact (horizontal build).
AM build variation and ultimately to functional performance; this will include evaluation of ISO 25178-2 parameters, together with parameters applicable to freeform and re-entrant surfaces, such as those proposed by Pagani [29].

6. Conclusions

A suite of surface-specific AM measurement artefacts has been proposed. These artefacts are small, economical to build and suitable for inclusion in every AM build. They include built-in manufacturing traceability and have been designed for easy measurement on standard metrology equipment. The artefact design may be tailored to the specific application to produce the greatest sensitivity to process changes. They may be used for process verification, to evaluate optimum build orientation and to generate information about the quantity and location of additional material required to allow the complete clean-up of the surfaces during post-processing.

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