Additive manufacturing and non-destructive testing of topology-optimised aluminium components

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ABSTRACT
Additive manufacturing (AM) unlocks novel industrial possibilities in relation to design optimisation for lightweight structures, e.g. in aerospace applications. However, the inherent geometric complexity of topology-optimised AM components represents a major challenge for conventional non-destructive testing (NDT) methods. Due to its flexibility and high throughput, industrial X-ray micro-computed tomography (XCT) is the most promising NDT method for AM. In this contribution, we investigate topology-optimised engine brackets that were manufactured from AlSi10 Mg using selective laser melting (SLM). We investigate the respective parts and in-process test coupons in a multiscale approach to be able to extract pore size distributions at different spatial resolutions between 105 and 1.25 µm isometric voxel size. At the lowest spatial resolutions, existing pores cannot be segmented. In contrast, decreasing voxel sizes leads to an increase in total porosity up to 1.53%. Defects like pores in load-carrying areas can profoundly influence the component’s mechanical performance; hence, extensive NDT investigations are mandatory to predict the effect of defects in aluminium AM components.

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Introduction
Commercial aviation and particularly space flight hardware premise high demands on performance and reliability of applied lightweight structures. Main challenges in the manufacturing of failure safe aerospace materials and structures involve component design and optimisation, (micro-) structural characterisation, analysis of thermo-mechanical behaviour and structural health management [1]. In general, engineering applications in aerospace require high levels of process control, inspection, qualification test criteria and knowledge about material properties and are characterised by strict design tolerances and safety concerns, e.g. in relation to the impact of defects.

Using additive manufacturing (AM), complex metal components with internal geometries can be produced without the need for joints or welds simultaneously consuming less raw material and energy than traditional manufacturing techniques [2]. A major precondition to facilitate the potential of advanced manufacturing processes like Selective Laser Melting (SLM) are powerful NDT methods for the inspection of...
microstructural features and overall geometry, e.g. in relation to porosity and warpage [3]. SLM is a powder bed-based welding process, hence challenges in relation to powder quality, surface roughness and cleanliness level assessment occur. Before employing AM technology in a broader range of aerospace applications, further efforts – e.g. in relation to establish ECSS standards for AM [4] – need to be tackled including material development and characterisation, process modelling and control, precision and resolution, construction time constraints and costs, as well as machine qualification, certification and standardisation [5].

Current NDT procedures of AM parts are the same that are applied to conventionally wrought, forged and moulded metal components. However, a wide range of NDT challenges for AM parts have to be addressed: (a) complex part geometry, (b) surface finish, (c) internal faults (d) and a widespread lack of defined critical defect types and sizes, (e) physical NDT reference standards, (f) written inspection procedures tailored for AM processes and (g) probability of detection data.

This also applies to advanced approaches in component design and manufacturing using topology optimisation to generate light-weight parts while preserving mechanical strength [6]. Topology optimisation tools are applied to produce structures with complex geometries that are shaped in regard to specified loading regimes using a least-weight and performance design [7]. Using AM, it is possible to generate such complex shape geometries directly, transferring design concepts to a part without the constraint of traditional manufacturing like milling. However, NDT of metal components with complex shape is challenging for standard inspection methods like Eddy current or radiographic testing.

In contrast, X-ray microcomputed tomography (XCT) is well suited for the evaluation of complex part geometries while being flexible to fulfil materials, design and test standards encountered throughout a component’s life cycle. Due to its rapidness, flexibility and high throughput industrial XCT is the most promising NDT method for topology-optimised AM metal components. Moreover, XCT provides three-dimensional models of the scanned part that can be used in finite element (FE) simulations, e.g. to predict the influence of detected defects on fatigue life [8].

This contribution used freely available CAD data of a real aerospace component that was optimised for weight reduction in order to investigate the microstructure of an actual AlSi10 Mg part produced by SLM. To ensure optimal image quality for the scan of the complete part, we used two different XCT simulation approaches to determine the part’s optimal scanning orientation and scanning parameters at a voxel size of 105 µm. Subsequently, we firstly extracted a safety critical region a clevis arm of one bracket that represents the region where the external force is applied and is thus subjected to high-stress levels during mechanical loading. Secondly, we cut-out of the component a smaller region (318.75 mm$^3$) from the clevis arm for high-resolution scans. Parts of the cut-out were scanned at increasing higher physical resolutions (voxel sizes: 65, 20, 10 and 5 µm). Additionally, we investigated in-process samples at corresponding voxel sizes down to 1.25 µm to identify (micro-) pores that cannot be detected at a low physical resolution. To visualise the influence of voxel size on the detectability of pores, we computed pore size distributions for an in-process sample.
Materials and methods

Part geometry is based on a topology-optimised engine bracket originally designed to be manufactured from titanium (M Kurniawan, GE Jet Engine Bracket Version 1.2) [9]. The size of the complete bracket is 177.90 mm in width, 107.95 mm in depth and 62.51 mm in height.

Additive manufacturing

Two brackets together with in-process samples (rods) of 1.6, 2.5 and 4 mm diameter were produced from AlSi10 Mg by SLM using an EOS M400 system. Build orientation and support design of the brackets were defined in Materialise Magics®. The final orientation is shown in Figure 1. As-built reference rods (test coupons) were printed in the main build direction, i.e. the Z-axis in the Materialise Magics® coordinate system (see Figure 1), with a build height of 3 mm. Samples were manufactured with a set of custom parameters; hence, for certain parameters (laser power, scanning speed, hatch distance), detailed information cannot be disclosed. Average particle size was 45 ± 18 µm using a layer thickness of 50 µm. The temperature of the build platform was 45°C. A one-sided recoating strategy was applied. Heat treatment (200°C, 2 h duration) was employed for stress relieving while components were still attached to the build platform.

Support and connecting structures were removed by CNC machining before all surfaces were shot peened with stainless steel blasting material. Additionally, functional surfaces were milled to create realistic final parts (see Figure 2(a)).

Microcomputed tomography

Specimen placement

To find the optimal placement of the complete specimen on the rotary table of the XCT system, we used a visual analysis tool (Dreamcaster) developed by Amirkhanov et al. [10]. We used an STL file of the respective bracket containing 116,565 triangles faces (average edge length: 1.17 mm) that was imported into Dreamcaster. The number of projections was set to 720 while the angle range was 0–360°. From the resulting placement maps for average penetration, maximum penetration and bad Radon-area percentage, we chose two configurations with the lowest (‘good’ orientation) and highest (‘bad’ orientation) values of the weighted sum.

Figure 1. Print direction defined and optimised in Materialise Magics®.
To be able to scan the complete bracket in the determined orientation, a custom-made sample holder was designed in Autodesk Fusion360 and produced from PA12 using an EOS P 396 system housed at Fotec. It consists of an Euler cradle that is adjustable in two axes (see Figure 2(b)).

**XCT simulations**
Subsequently, we carried out a parameter study in order to determine optimal scanning parameters for the complete Al bracket in ‘good’ and ‘bad’ specimen orientation using *SimCT* [11]. Specimen geometry was represented by an STL model (triangulated mesh) that is assumed to be homogeneously filled AlSi10 Mg (density: 2.67 g/cm$^3$). Two different alignments of the complete bracket were virtually tested to find optimal values for voltage, current, pre-filter in front of the X-ray source and beam-hardening correction at a voxel size of 100 µm.

Image quality of the simulated volume data was quantitatively evaluated in terms of a histogram-based image quality measure (Q-factor) [12]. In contrast to signal-to-noise (SNR) and contrast-to-noise (CNR) ratio this metric takes quality reducing effects like noise and all kinds of artefacts into account and does not necessarily need an experienced user that defines explicit regions for optimisation. Power was limited to 100 W to prevent the target from thermal destruction while voltage was incrementally increased in steps of 20 kV from 120 to 220 kV. Current was adapted accordingly. Scanning parameters were optimised for a maximum integration time of 2400 ms and 1800 projections to achieve a reasonable scanning time less than 2.5 h. Additionally, we investigated the influence of pre-filtering (0.5 mm Cu) and beam-hardening correction (implemented in the Rayscan 250E reconstruction software) on image quality. The results of the parameter study are displayed in Figure 3.

**XCT scanning protocols**
Scanning parameters for the evaluation of the complete specimen are reported in Table 1. Both complete brackets were scanned at a voxel size of 105 µm using a Rayscan 250E system that is equipped with a Viscom 225 kV microfocus X-ray source and a Perkin
Elmer 1024 × 1024 a-Si panel matrix detector. XCT datasets were reconstructed using the filtered back-projection algorithm integrated into the Rayscan reconstruction software.

The difference in voxel size between simulations and actual scans is due to the fact that it was not possible to use the complete effective detector area in vertical direction in the

**Figure 3.** Scan parameter analysis in SimCT: Q-factors for the analysed combinations of tube voltage, pre-filter and beam-hardening correction (BHC) for two specimen placements (‘good’ and ‘bad’ orientation) that were determined in Dreamcaster (see materials and methods section). The vertical black arrow refers to the parameter and post-processing combination that yielded the highest Q factor, i.e. best image quality, that was using for the XCT scans of the complete bracket.

<table>
<thead>
<tr>
<th>XCT system/parts</th>
<th>VS</th>
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<th>t</th>
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<tr>
<td><strong>Rayscan 250E</strong></td>
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<tr>
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<td>200</td>
<td>500</td>
<td>2400</td>
<td>1800</td>
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<tr>
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<td>325</td>
<td>3000</td>
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<tr>
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<td>140</td>
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<td>500</td>
<td>2400</td>
<td>5</td>
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<td>lug (cut-out)</td>
<td>10</td>
<td>140</td>
<td>180</td>
<td>500</td>
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<td>lug (cut-out)</td>
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<td>140</td>
<td>180</td>
<td>500</td>
<td>2400</td>
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<td>500</td>
<td>2400</td>
<td>5</td>
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<tr>
<td>in-process sample (2.5 mm)*</td>
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<td>140</td>
<td>40</td>
<td>800</td>
<td>2400</td>
<td>5</td>
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*In-process sample was scanned at all voxel sizes with shown parameters.

Table 1. Scanning parameters: voxel size (VS) in (µm)³, voltage (U) in kV, current (I) in µA, integration time (t) in ms, number of projections (proj) and averaging (avg).
Rayscan reconstruction software compared to SimCT. Hence, voxel size was slightly increased to 105 µm for the actual scans to have a safety margin for specimen placement. In addition to the scans of the complete specimen, region of interest scans were carried out at a voxel size of 65 µm. Scanning parameters were adapted accordingly (see Table 1).

Subsequently, the clevis arms of one bracket were removed using wire-cutting in order to carry out higher resolution scans of this region at 20 µm voxel size using a Nanotom 180NF (GE phoenix | X-ray) system. Two scans were necessary to scan each complete clevis arm. Finally, an arbitrarily defined region of the lug (8.5 x 7.5 x 5 mm) was cut out to be able to perform higher resolution scans of the cut-out at 10 µm and 5 µm isometric voxel size, respectively.

Reference rods in build direction (Z-direction, see Figure 1) were scanned together with the complete brackets at voxel sizes of 105 µm and 65 µm voxel sizes. Additionally, one rod (2.5 mm diameter) was scanned at voxel sizes of 20, 10, 5, 2.5 and 1.25 µm. Volume data were reconstructed using filtered back-projection applying a beam-hardening correction using the GE phoenix software Datos | x.

Porosity in each sample was extracted from obtained, unfiltered volume data using the porosity/inclusion analysis module in VGStudioMax 3.3 (Volume Graphics). We manually defined a global threshold using the respective Iso50 (defined as the mean value, i.e. 50%, between the peaks of air and material) and set the minimal pore size (volume) to 27 voxels. Porosity is visualised in terms of pore diameter. Furthermore, we computed the minimal edge distance of each pore. Plots and histograms were generated in RStudio (Version 1.2.5033) and Matlab 2018b.

**Results**

Using equally weighted parameters in Dreamcaster, the optimal placement (‘good’ orientation) of the complete bracket was determined at Rotation X of 165° and at Rotation Z of 75°. The weighted sum for the ‘bad’ orientation was determined at Rotation X of 90° and at Rotation Z of 90°.

Using SimCT, we ran an XCT scan parameter analysis for both specimen placements (referred to as ‘good’ and ‘bad’ orientation) of the complete bracket. Figure 3 displays the Q-factors for the respective combinations of sample placement, voltage, pre-filter and beam-hardening correction. The highest Q-factor was found for the simulated scan of the complete bracket in the ‘good’ orientation, using a tube voltage of 200 kV, no pre-filter, while applying a beam-hardening correction (Q-factor: 7.40). The lowest Q-factors are observed for scans in ‘bad’ orientation applying a 0.5 mm Cu filter without BHC (Q-factor: 3.82–4.15). The lowest Q-factor of 0.73 was found for the simulated scan with a voltage of 120 kV in ‘bad’ orientation without pre-filtering. This value is not depicted in Figure 3 to prevent a compression of the rest of the data points in the plot. In general, simulated scans in ‘good’ orientation delivered higher Q-factors than scans in ‘bad’ orientation except for unfiltered and uncorrected scans in the ‘good’ sample orientation. Based on the results from the placement and scan setting simulations, the complete brackets were scanned in ‘good’ orientation using BHC while omitting a pre-filter using the scan parameters reported in Table 1.

Figure 4 shows a volume rendering of the corresponding actual XCT scan of the complete bracket. A visual inspection of the volume data showed no major surface faults.
or internal pores that could unequivocally be identified as defects in the volume data at a voxel size of 105 μm. However, beam-hardening artefacts are clearly visible in the slice image shown in Figure 4(b) in the lower hole region of the depicted clevis arm and along the cutting planes of the planar material profiles, e.g. the base plate at the bottom of Figure 4(b). Strong beam-hardening artefacts can also be observed at intersections of horizontal and vertical walls that intersect each other, e.g. the base plate and vertical plane in the region below the lug hole. Qualitatively, pores could be visually detected in the volume data of an ROI scan of the clevis area at a voxel size of 65 μm. However, at this low physical resolution, it is not possible to quantitatively extract pores since none of the visually identifiable pores is comprised of more than 27 voxels (defined detection threshold in VGStudioMax 3.3).

At a voxel size of 20 μm, it was possible to segment internal pores in the cut-out clevis arm over the whole sample volume, e.g. the lug hole region of the bracket. Figure 5 visualises the result of the porosity analysis of the detached clevis arm. The complete clevis arm has a material volume of 4501.6 mm$^3$. Defect volume amounts to 5.6 mm$^3$, resulting in a porosity of 0.1% that is represented by a total of 7729 detected pores with a mean diameter of 158.42 μm (standard deviation: 47.34 μm). Mean sphericity is 0.60 (± 0.05) while the mean minimal distance from the pore’s centre to the outer edge of the part is 221.09 μm (± 64.62 μm). Even though pores can be found all over the clevis arm, near-surface porosity is most prominent. While milled surfaces in the circumference of the inner lug hole show a low level of porosity, a large amount of pores is located near the surface (highlighted with black arrows in Figures 5 and 6).

Figure 6 shows a higher resolution scan of the region detailed in Figure 5 at a voxel size of 5 μm. The region of interest is characterised by a porosity of 0.5% that is represented by a total of 13,318 pores with a mean diameter of 44.07 μm and a standard deviation of 24.80 μm. Mean sphericity is 0.62 (± 0.07) while the mean minimal distance of the pore’s centre to the outer edge of the component is 266.09 μm (± 185.97 μm). As shown in Figure 5, the majority of pores can be found in the contour region (indicated by black arrows in Figure 6). In contrast, machined surfaces are characterised by the absence of a distinct region showing predominantly near-surface porosity.

Figure 4. Topology-optimised AlSi10 Mg engine bracket. (a) 3D volume rendering of the complete part scanned in ‘good orientation’ without a pre-filter but using BHC (voxel size: 105 μm; see Table 1 for scan parameters). The cutting plane of slice image is represented by dashed red lines. (b) XCT slice image through the left clevis arm according to the cutting plane shown in (a). Yellow arrows indicate regions of strong showing beam-hardening artefacts.
Figure 5. Pore size distribution in the left clevis arm (side view) that was removed from the bracket and scanned at a voxel size of 20 µm. Pores cluster in the region close to the surface of the part, as shown in the detailed view. Black arrows highlight near-surface porosity.

Figure 6. Detailed porosity analysis in a cut-out of the left clevis arm scanned at a voxel size of 5 µm. (a) Side view of the whole clevis arm indicating the position and dimensions of the extracted ROI and (b) pore size distribution (in diameter) in the respective ROI showing a high amount of near-surface porosity.
To be able to quantify the effect of scanning resolution on determined porosity values, we compared an in-process sample that is represented by a rod with a diameter of 2.5 mm. This reference sample was scanned at voxel sizes between 105 µm and 1.25 µm (see Table 1). Figure 7 displays XCT slice images in (top view) showing that even at low physical resolutions (105 µm and 65 µm) large pores are visible, e.g. at the bottom of each image.

Starting from a voxel size of 20 µm, it is possible to segment the largest existing pores in the cylindrical reference sample. Table 2 summarises the results of the porosity analysis for the same sample scanned with different voxel sizes in a defined ROI. The outline of the analysed region of interest was defined by the samples outer surface. The total height of the ROI that was extracted for all data sets was 1.15 mm. ROI dimensions were governed by the field of view (FOV) of the scan at the highest scanning resolution (voxel size: 1.25 µm). This resulted in a total analysis volume of 5.6 mm$^3$.

Pores can be detected segmented at a voxel size of 20 µm resulting in a porosity value of 0.43%. A total of 25 pores were detected at this scanning resolution. At a voxel size of 10 µm, porosity is 0.94% represented by 94 pores in total. Even though porosity values between 5 µm (1.19%), 2.5 µm (1.40%) and 1.25 µm (1.53%) voxel size only increase slightly, the number of detected pores steeply rises from 720 to 7587, and 35,572, respectively.

![Figure 7. Comparison of slice images of a cylindrical in-process sample with a diameter of 2.5 mm. At low physical resolutions (a and b) it is not possible to unequivocally detect pores in this sample. At higher resolutions (c–g) pores can be segmented in varying levels of accuracy.](image)

<table>
<thead>
<tr>
<th>Voxel size in µm</th>
<th>Porosity in %</th>
<th>Number of detected pores</th>
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<tr>
<td>105</td>
<td>0.0</td>
<td>0</td>
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<tr>
<td>65</td>
<td>0.0</td>
<td>0</td>
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<tr>
<td>20</td>
<td>0.43</td>
<td>25</td>
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<tr>
<td>10</td>
<td>0.94</td>
<td>94</td>
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<tr>
<td>5</td>
<td>1.19</td>
<td>720</td>
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<tr>
<td>2.5</td>
<td>1.40</td>
<td>7587</td>
</tr>
<tr>
<td>1.25</td>
<td>1.53</td>
<td>35,572</td>
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</table>

Table 2. Porosity value in an ROI of a cylindrical in-process sample with a diameter of 2.5 mm at different voxel sizes.
The relationship between physical resolution and the maximum diameter of detected pores was analysed for the ROIs described in Table 2. The barplot in Figure 8 subdivides pores with a given diameter into classes between 2–6 µm (centre: 4 µm), 6–11.5 µm (8 µm), 11.5–22.5 µm (15 µm), 22.5–45 µm (30 µm), 45–90 µm (60 µm), 90–180 µm (120 µm) and above 180 µm (240 µm). The values on the abscissa represent the respective centre values (see brackets). Pore diameter ranges were defined in accordance with the used voxel sizes. Since the amount of detected pores was high, particularly for the highest scanning resolution (1.25 µm voxel size), we used a logarithmic ordinate scale for visualisation of the results.

While large pores with a diameter >90 µm can unequivocally be detected at a resolution of 20 µm, it is necessary to double increase the physical resolution to 10 µm to detect pores with a diameter >45 µm. The smallest detected pore diameters at a voxel size of 20 µm and 10 µm were 99.50 µm and 46.78 µm, respectively. Pores with a diameter >11.5 µm were detected at a voxel size of 5 µm. However, the majority of pores show a diameter <11.5 µm. To detect pores between 2 µm and 11.5 µm it is necessary to scan the respective sample at the highest feasible resolutions, i.e. 2.5 µm or 1.25 µm for the analysed reference rod of 2.5 mm diameter. Furthermore, at lower spatial resolutions, the

![Figure 8. Pore diameter (in classes; centre value of each class is plotted on the X-axis) versus frequency (log scale) in an ROI of an in-process reference sample (diameter: 2.5 mm). At low scanning resolutions, only the largest pores can be detected. Pore detectability, particularly of small pores, increases with lower voxel sizes.](image-url)
diameter of a pore may be underestimated due to the partial volume effect. While the largest pore detected at 20 µm voxel size has a diameter of 208.52 µm, the largest pore segmented at a voxel size of 1.25 µm has a diameter of 281.74 µm. At low scanning resolutions, the edges of pores that are partially filled with half-molten material may not be clearly distinguished and segmented as two or more separate pores. Hence, a direct comparison of absolute pore frequency in our analysis would be misleading since pores labels are not necessarily the same between the data sets.

Discussion

To guarantee the best possible image quality of XCT volume data, it is often necessary to perform several test scans to elucidate the optimal combination of scanning parameters that influence the outcome of a scan. To overcome this issue, we determined the optimal scanning orientation of the complete sample using Dreamcaster [10]. Since laboratory X-ray sources produce a polychromatic spectrum, the mean energy of the generated X-ray beam increases as it passes through an object since lower energy photons are attenuated at a higher rate than higher energy photons (beam hardening). This physical effect can cause two types of artefacts: (1) so-called cupping artefacts and (2) the appearance of dark and bright bands or streaks [13] that degrade image quality. Optimal specimen placement can significantly improve image quality by reducing beam-hardening artefacts. This was achieved by minimising the penetration lengths and the total surface area of the planar faces with improper reconstruction of the respective ('good') placement [14]. To be able to compare the results of the subsequent scanning parameter study, we additionally investigated a suboptimal ('bad') specimen orientation.

Since the quality of a real XCT scan is mainly determined by the applied scanning parameters, we investigated the effect of parameter choice on image quality using XCT simulations. Using SimCT [11], we carried out a parameter study to estimate the combination of parameters that deliver the best image quality, expressed as Q-factor [12], for the scans of the complete brackets in a reproducible way. The limiting factor in this parameter study was total scan time (fixed to 135 min) that was chosen to be able to carry out the actual XCT scans in a reasonable time. Highest Q-factors were found for the scans of the complete brackets in good orientation at 200 kV without the employment of a pre-filter but using the integrated beam-hardening correction from the Rayscan reconstruction software. Higher values for the combination of (1) no pre-filter and BHC compared to (2) a 0.5 mm Cu pre-filter and no BHC are due to the higher levels of noise introduced by a loss of photons at the detector when using a pre-filter in front of the X-ray source. Increasing total scan time would result in an increase of Q-factor for the latter combination.

The detectability of pores at low spatial resolutions is very limited, e.g. when part size limits scanning resolution – even if image quality is high. The minimum pore diameter that can unequivocally detected is at least three voxels wide, i.e. it comprises at least 27 voxels in three dimensions [2]. According to this rule, the minimum detectable pore size in the scan of the complete bracket at 105 µm voxel size is ≥315. However, the largest detected pore in the analysed cylindrical in-process test coupon had a diameter of 281.74 µm.
To overcome this shortcoming, it is recommended to use witness specimens/test coupons that are produced in the same build cycle as the part under investigation [15]. In this study, we evaluated the porosity in a cylindrical test coupon with a diameter of 2.5 mm that was scanned at high resolution up to 1.25 µm voxel size. However, results from the analyses of scans of a cut-out of the actual part and test coupons at the same spatial resolution (5 µm) show deviating values of porosity, 0.5% and 1.19%, respectively. One reason for the difference is the physical post-processing of the actual components using heat treatment, shot peening, steel blasting and machining of functional surfaces, including the lug region that was investigated. Hence, porosity in post-processed parts may be significantly lower than in as-build test coupons that are too small to be post-processed. This has to be considered when extrapolating from in-process reference samples to the actual parts, even if they were generated in the same build cycle.

Presumably, the huge amount of small pores detected by XCT in the surface-near edge region of the AM engine brackets under investigation has a huge negative impact on fatigue properties that are predominantly influenced by the contour in the first hundreds of microns from the surface [16]. These findings highlight the need for extensive NDT investigations that facilitate the prediction of the effect of defects in aluminium AM components. An advantage of XCT is the provision of three-dimensional volume data that can be used for simulation studies on fatigue life of AM parts using FEA.

**Conclusion**

Although AM offers high flexibility in the production of complex components, it can be difficult to control the porosity of the internal microstructure. In this work we analysed topology optimised AlSi10 Mg components and test coupons that were manufactured using SLM. Using a multiscale approach, we found that existing pores cannot be unequivocally detected or segmented at the low spatial resolutions above 65 µm. At higher scanning resolutions, we found porosity values up to 1.53% at a voxel size of 1.25 µm. Those findings support the effort to create an information base for AM qualification, certification and standardisation.

**Disclosure statement**

No potential conflict of interest was reported by the author(s).

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