A Novel Tomographic Characterisation Approach
for Sag and Dross Defects in Metal Additively
Manufactured Channels

Markus Baier, Mirko Sinico, Ann Witvrouw, Wim
Dewulf, Simone Carmignato

PII: S2214-8604(21)00057-9

DOI: <https://doi.org/10.1016/j.addma.2021.101892>

Reference: ADDMA101892

To appear in: *Additive Manufacturing*

Received date: 17 September 2020

Revised date: 31 January 2021

Accepted date: 2 February 2021

Please cite this article as: Markus Baier, Mirko Sinico, Ann Witvrouw, Wim Dewulf and Simone Carmignato, A Novel Tomographic Characterisation Approach for Sag and Dross Defects in Metal Additively Manufactured Channels, *Additive Manufacturing*, (2020)
doi:<https://doi.org/10.1016/j.addma.2021.101892>

This is a PDF file of an article that has undergone enhancements after acceptance, such as the addition of a cover page and metadata, and formatting for readability, but it is not yet the definitive version of record. This version will undergo additional copyediting, typesetting and review before it is published in its final form, but we are providing this version to give early visibility of the article. Please note that, during the production process, errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

A NOVEL TOMOGRAPHIC CHARACTERISATION APPROACH FOR SAG AND DROSS DEFECTS IN METAL ADDITIVELY MANUFACTURED CHANNELS

Markus Baier ^{a,*}, Mirko Sinico ^{b,c}, Ann Witvrouw ^{b,c}, Wim Dewulf ^b and Simone Carmignato ^a

^a Department of Management and Engineering, University of Padova, 36100 Vicenza, Italy

^b Department of Mechanical Engineering, KU Leuven, 3001 Leuven, Belgium

^c Member of Flanders Make - Core lab MaPS, KU Leuven, 3001 Leuven, Belgium

Abstract

Channels and bores in metal components produced by laser powder bed fusion (LPBF) are internal features that are typically affected by defects such as dross and sag formation, dimensional errors and global deformations in different proportions. Such deviations from the ideal geometry may strongly limit the functionality of the channels, but are difficult to prevent, due to complex multi-physical production aspects. Different destructive and non-destructive approaches are available to investigate the geometry of the internal features and possibly correlate their results to the LPBF process parameters; however, such approaches do not offer a systematic method to derive key characteristics of the main contributors for channel deviations. Hence, this work proposes a novel tomographic non-destructive analysis of LPBF channels and bores, focusing on the derivation of sag and dross key parameters. The methodology works on polar-transformed profiles obtained from image stacks which are extracted perpendicularly to the channel axis from the X-ray computed tomography (CT) reconstructed volume. The method allows for the clear determination of surface characteristics and includes the quantitative evaluation of descriptors through an algorithm specifically developed for the purpose. In particular, general form deviations are addressed by fitting sinusoidals on the unwrapped mean surface profile, to tackle deviations induced by thermal residual stresses. Proposed descriptors of sag and dross are the onset angle of protrusions, separation criteria between sag and dross effects, and the peak analysis of the mean profile after approximation with a least squares spline. The developed algorithm is tested in the case study of a LPBF AlSi7Mg0.6 benchmark part comprising hollow cylinders and inter-connecting frusta with different diameters. The resulting evaluation of the benchmark part also corroborates how the proposed methodology can help to obtain more precise information regarding the correlation of LPBF fabrication conditions and obtained channels geometrical deviations. Furthermore, the results show possible routes to enable an a-priori compensation of the nominal channel design for first-time right LPBF manufacturing.

Keywords; Metal additive manufacturing, computed tomography, cooling channels, improving precision, feedback for design, powder bed fusion

* Corresponding author at: Department of Management and Engineering, University of Padova, 36100 Vicenza, Italy

Email addresses: markus.baier@unipd.it (M. Baier), mirko.sinico@kuleuven.be (M. Sinico),

ann.witvrouw@kuleuven.be (A. Witvrouw), wim.dewulf@kuleuven.be (W. Dewulf), simone.carmignato@unipd.it (S. Carmignato)

1. Introduction

Laser Powder Bed Fusion (LPBF) is more and more used in the manufacturing of metal components thanks to its advantages such as design freedom, reduced waste material, short manufacturing lead times and high flexibility. Moreover, compared to other metal Additive Manufacturing (AM) technologies, LPBF is the most common employed process both in industry and academia, by reason of its relatively low cost, wide material choice and the ability to produce near-net-shaped parts ready to use [1–3]. The powder metal additive process is being slowly implemented in manufacturing systems for advanced components in high-value sectors such as aerospace, automotive and defence [1,4], as a result of the considerable research investments and the developments throughout the whole metal AM value chain. Advancements have been reported starting from the qualification of the powder raw material [5] and the introduction of industrial standards, e.g. ASTM F42 and ISO/TC 261 standardization efforts [6,7], down to the end of the chain where quality control has been improved via non-contact measurement methods, such as industrial X-ray computed tomography (CT), photogrammetry, laser scanning and structured light 3D scanners [8–10]. At the same time, LPBF machines and their Human-

Machine Interface (HMI) and preparation software have seen clear developments towards automation, in-process control and higher production throughput [11].

However, despite the steps taken to make LPBF a reliable manufacturing process, this technique still shelters some intrinsic challenges to meet the precision requirements demanded for several applications [12]. Typical limitations are: limited geometrical accuracy, sub-optimal surface quality, layering steps in the building direction, thermal residual stresses plus thermal shrinkages [13] and sag and dross defects on unsupported overhanging surfaces [14]. Concerning sag and dross defects, design guidelines and rules have been established [15–17] to define maximum overhang angles depending on the LPBF machine, processing parameters and material used. Below this maximum angle, supporting structures have to be placed to minimize the formation of protrusions, which are fostered by low conductive powder below the scanned layer. Although the terms indicating these protrusions, i.e. sag and dross, are used interchangeably throughout the available literature, in this paper we define the dross as the melting of excess material in overhanging surfaces caused by overheating and often spanning multiple LPBF layers [18]. Sag defects are instead defined as a minor curvature or bulge at the bottom of the laser melted track due to small unsupported areas, and are dimensional errors smaller in size than the average melt-pool depth, i.e. often not spanning more than one or two layer thicknesses. Both these defects can be counteracted with adequate supporting, by providing heat dissipation and a rigid substratum. Moreover, the rigid link between the part and the building platform helps to prevent the warping due to residual stresses.

While the use of supports is effective and has been accepted as a cost to pay to successfully fabricate LPBF parts, supports are often not a viable solution for internal structures or cooling channels, where removal of the supporting structure is difficult, complicated, or even impossible. Without the use of supports, design limits such as maximum channel diameter, channel shape and channel orientation are directly affected by the minimum LPBF overhang angle constraint and heat accumulation related phenomena during LPBF fabrication. Consequently, designers need to be extra careful in the conception of AM parts where channels play an important functional role. For instance, in the moulding sector, channel paths and channel shapes are optimized in additively manufactured moulds and mould inserts to improve the mould thermal management, thus decreasing the mould cycle times [19,20]. However, the freeform paths of the channels, which follow the shape or profile of the mould core or cavity, impedes mechanical accessibility to remove internal supports. Similar, conformal cooling approaches are also important for gas turbines and electronic components. This leads to the necessity of a better understanding of defect formation for such common and vastly utilised specific features as channels and bores, since the available LPBF design guidelines for these features are often generalised and do not really reflect the full capabilities of the process.

If in-depth knowledge is gathered on the channel's deformations and defects evolvement, a-priori design corrections can be envisioned, or LPBF process parameters can be adapted [21] to achieve tighter geometrical tolerances with lower deviations from the nominal Computer Aided Design (CAD) file. The understanding of the defects and their correction/compensation can be accomplished by multiple means, spanning from in-depth simulations [22] to experimental trials and errors. The following paragraphs give a glimpse on recent progress regarding tomographically based Non Destructive Testing (NDT) of AM parts and show how the acquired 3D information can be used for defect assessment and possibly exploited to devise correction methods for channels and bores.

The analyses of deformations and defects of channels and bores produced by LPBF have been growing topics of interest, given the necessity to push the AM fabrication process towards higher precision and accuracy. The state of the art has advanced in understanding how a certain channel geometry develops depending on LPBF processing parameters, build direction and channel dimension, whereas the concurrent development of industrial CT for the non-destructive inspection of parts strongly fostered the recent advances. For example, a preliminary study from Kempen et al. [23] used CT inspection to quantitatively determine the dimensional errors of AlSi10Mg channels and to demonstrate how dross formation develops for horizontal channels with diameters from 0.5 mm to 2.5 mm. The conclusions of the work were that all channels need dimensional compensation, but – due to the sag and dross defects – non-vertically oriented channels also need compensation

for roundness errors. Further on, Snyder et al. [24,25] were able to apply CT to measure the dimensional errors of LPBF channels, as well as their surface roughness and geometrical errors including concentricity and circularity deviations. Their conclusions were in line with the results by Kempen et al. [23], with additional insights about the surface roughness, which had its minimum for the vertical build direction. Their comparison between 45° and horizontally oriented channels showed that both directions produced similar channels for their material (Inconel 718) and LPBF setup, whereupon channel diameter roundness and internal roughness were investigated. The applicability of CT inspection to derive local surface texture information of internal features was later on assessed by Thompson et al. [26,27]. Their studies concentrated on the comparison between CT analysis and optical surface measurements, showing how CT data can be a viable alternative for topography measurements, even if it needs to be handled with care. Similar conclusions were also found by Townsend et al. [28] and Zanini et al. [29]. However, their studies were performed on external AM surfaces. More recently, Klingaa et al. [30,31] extended the CT analysis to internal surfaces of LPBF channels, by modelling the roughness value depending on the defined global build orientation (α) and local orientation (β). This approach allows establishing novel concepts, like the presented rough belt concept with an angular width, which showed how the angular width directly correlates to the α -orientation. Moreover, through the full CT 3D surface topography and the disclosed methodology, influences down to a singular line track or layer step can be derived.

Only a limited body of work has been found in literature regarding a-priori compensations of LPBF channels to meet the target nominal CAD geometry, caused by the intrinsic difficulty to directly correlate defect formation and surface topography evolution with an efficient and reliable compensation model. In many cases, researchers have tried to minimize the most pronounced deviations, i.e. dross and sag defects in the overhanging areas, by radically redesigning the circular section of channels to a self-supporting “teardrop” profile [15,25,32]. Others applied a complete shift of the circular section towards diamond, split-circle, or other self-supporting geometries [16,25], whereupon a general suggestion of all studies was to build critical channels in the vertical building direction. Although the last option is only feasible for simple AM parts with straight channels or bores and favourable building orientations, the other two solutions have been consistently applied to overcome LPBF limitations.

However, for relevant applications such as connections or interfaces within assemblies, in case of LPBF applied for component replication (e.g. replacement of discontinued spare parts), or in special domains as microfluidics or heat-transfer devices with constraints on flow regime [33,34], a redesign of the final section is not a viable solution, because the manufactured channel or bore must adhere to the initially envisioned shape, most commonly circular. In such cases, precise quantitative information of the deviations from the nominal must be collected to determine a pre-print shape compensation.

The latter has been achieved only recently and for few materials, LPBF conditions and not for all encountered defects. Kamat and Pei [35] successfully derived a general analytical model to compensate the warpage (sometimes referred to straightening for channels) due to the thermal residual stresses. Their model was applied to build shape-compensated circular, elliptical and diamond shaped channels, but it tackled only the axial and bending deformation without taking in consideration the sag and dross defects. The same straightening effect and compensation were addressed by Paggi et al. [36] utilizing experimental data for the derivation of an angle dependent beam compensation parameter. Other investigations on developed residual stresses during LPBF [13] production could in theory as well be used to derive similar a-priori compensations. In relation to sag and dross compensation, without the aforementioned teardrop or complete redesign of the channel geometry, only Khan et al. [37] and Solyaev et al. [38] specifically investigated the necessary shape-compensation for these critical defects of the overhanging channel surface. Both researches used numerical simplified models to study the development of the defects; however, Khan et al. preferred to only tune the down-skin LPBF processing parameters, whereas Solyaev et al. suggested combining tuning of both parameters and an overcompensated channel geometry to obtain a close-to-nominal channel geometry.

Albeit researchers have demonstrated the value of CT analysis for the determination of internal features properties, for example to obtain general form or surface information, and a-priori geometrical compensation

methods are being developed, the state-of-the art analysis shows that no clear methods have been envisioned specifically for the experimental non-destructive determination of quantitative sag and dross defects properties. An advanced method is needed for complete geometrical characterization of peak deviations and position of the dross and for modelling of its form depending on build orientation and overhang angle as well as separation of the straightening effect from sag and dross, to better understand how the protrusions develop inside LPBF channels and bores. The experimental knowledge gained by such characterization could then be combined with simplified models, as the ones envisioned in [37,38], both to validate them and to increase their accuracy. If a quick methodology is made available to analyse all deviations (including straightening as well as sag and dross) induced by LPBF fabrication, a-priori channel compensations based on experimental data could be applied industrially. To address this challenge, this work presents a CT approach with micrometre resolution to obtain key information about channels and bores, mainly focusing on the derivation of the sag and dross properties and general form deviation. The latter is also addressed with a proposed a-priori compensation method based on the experimental results obtained from a purposely designed benchmark, which is presented below.

2. Materials and methods

2.1. Materials

The assessment of the novel analysis approach was performed on a LPBF benchmark part specifically designed for the scope of this work. The design comprises eight hollow cylinders and inter-connecting frusta with different diameters ranging from 2 mm to 16 mm in 2 mm steps and considers proper feasibility of CT measurements. Each cylinder has a wall thickness of 2 mm and a height of minimum 8 mm, with a total part length of 75 mm. The so-called “spyglass” test part is depicted in Figure 1, showing also the angled external flat surfaces on the 16 mm section, devised to facilitate surface texture measurements by linear profilometers as well as areal instruments.

Figure 1. (a) Isometric view of the spyglass benchmark CAD rendering with noted important dimensions; (b) Photo of the LPBF fabricated spyglass placed on the manipulator of the CT system, before scanning.

After the design stage, the spyglass benchmark was fabricated with a new aluminium alloy powder (3D Systems LaserForm[®] AlSi7Mg0.6) on a DMP ProX 320 machine with WIP (Work In Progress) machine parameters optimized for a layer thickness of 30 μ m. The part was built with the channel axis in parallel to the baseplate, i.e. in horizontal and at a small angle with respect to the re-coater direction and the air-flow, to minimise defects during the build. No supports were placed inside the channels of the part to mimic complex channel structures, which are inaccessible after the build and thus supports cannot be removed. Supports were only placed between

the part and the build plate and carefully removed after production. The defined benchmark was subsequently used to test the applicability of the novel CT investigation method for LPBF channels.

2.2. Methods

This section shortly explains the most important instruments and performed measurements, including a detailed explanation of the different evaluation steps which were performed using the developed evaluation algorithm.

2.2.1. Roughness measurements

Surface profiles were acquired with a Taylor Hobson Form Talysurf 120L profilometer equipped with a 60° conic probe ending in a 2 µm radius ball, whereas filtering of the raw data was performed following the ISO standards (ISO 4287:1997 and ISO 4288:1996) [39,40]. The measurement of each profile has been repeated 5 times at different locations on each of the flat surfaces (Figure 1a, 16 mm section), in direction of the cylinder axis (Figure 1a, red arrow), to gain information about the angular dependence of the surface roughness. The resulting Ra roughness parameter is only reported to aid the discussion on the exported CT surface profiles in section 3.3.

2.2.2. X-ray computed tomography scans

A Nikon XTH 225ST (Nikon Metrology X-Tek, UK) CT was utilised to acquire the 3D scan of the benchmark. The spyglass part was centred on the rotary table of the CT machine, standing upright on the largest cylinder with the cylinder axes in parallel to the vertical direction as shown in Figure 1b. This allowed to move the part very close in front of the X-ray source and the distance was chosen to ensure that the largest channel section was completely visible on the 2000x2000 pixels detector screen. As a result, a constant voxel size of ~10 µm was achieved, as the part's features were magnified 18.5× onto the flat-panel detector due to the cone beam geometry for all separate scans of the spyglass sections.

As a consequence of the height of the part standing upright, it was necessary to carry out separate scans for each cylinder section including an overlap between the different scans, allowing for later registration and fusion of the single datasets into one volume containing the entire part. Thus, for this benchmark, a total of 8 CT scans were performed. The parameters of the scans were optimised for the two extremes of the part, i.e. the section with the smallest and the biggest diameter and were fixed to a voltage of 130 kV, a power of 6 W and exposure time of 1000 ms, acquiring 3600 projections for each scan. Thanks to the low power, the focal spot size of the X-ray source is minimized and can be assumed to be smaller than 3 µm according to the manufacturer. For this reason, it is a valid assumption that the spot-size has no influence on the resolution, as it is three times smaller than the voxel size. In addition, the amount of projections per scan assures that no image quality degradation was introduced by a limited number of projection views [41]. Furthermore, a scan of the reference sample described in [42] (called “fish-eggs” artefact) was acquired at the same voxel size. The sample contains calibrated features, which allows to calculate a voxel scaling factor to compensate for possible scaling errors during the multiple batch scans.

After CT scanning, each CT dataset was reconstructed and subsequently loaded in the analysis and visualization software VGSTUDIO MAX 3.1 (Volume Graphics GmbH, Germany) for further processing. The surface of the separate volumes was determined using the ISO50 threshold and the volumes were registered and aligned with the aid of the overlapping regions, containing surface features that are utilised by the software for proper alignment, and subsequently merged to obtain one single volume containing all spyglass sections to allow the evaluation of the entire sample. The merging was necessary to be able to conduct an analysis such as an “actual-to-nominal” comparison on the full sample, as the analysis can only be performed on a single volume.

2.2.3. Actual to nominal comparison

The nominal geometry used for part production was then imported and at first aligned manually with the reconstructed volume. A Gaussian best fit registration for the whole part was conducted twice between the nominal model and the region of interest (ROI) first with rough precision and afterwards with the highest precision selectable in the VGSTUDIO software. In this way, the actual to nominal comparison of the full part enabled a more precise visualisation of the part distortions with respect to the general channel axis of the spyglass artefact.

2.2.4. Cylinder fitting and image stack extraction

Cylinders were fitted, with a Gauss least squares method, on the five smallest internal channel sections, cf. Figure 1a, which are, according to AM guidelines [15–17], channels with diameters which can be built consistently without internal supports. It was necessary to determine the channel axis of each channel section separately, as a single axis could slightly deviate from the main channel axis of the CAD due to warpage of the part during build and after removal from the base plate, or due to misalignment between the CAD and the CT volume. Hereby special care had to be taken to select only surface points in the areas of the channels with the least deviations, i.e. the areas corresponding to the lower half of the channels, avoiding line-tracks or partially sintered residual powder particles in the bottom area of the channel.

Afterwards, two new cylinders with the internal and external nominal diameter of the respective spyglass section were created around the axis of the previously fitted cylinders. Subsequently, the volume was separately aligned for each cylinder section, with the cylinder axis coinciding with one of the main coordinate axes and the support structures facing downward. In this way, it is possible to ensure proper alignment and to extract cross-sectional images of the channels perpendicular to the channel axis. To reduce the size of the output files, the volume data were unloaded leaving only the surface visible in the sectional views. Afterwards, cross-sections with a distance equal to the voxel size, i.e. 10 μm , were extracted over a range of 7.8 mm along each channel axis, whereas the range was centred around the middle of each channel section to avoid the zones close to the ends of the respective channel, cf. Figure 1a, resulting in five stacks with 780 cross-sections per spyglass section.

2.2.5. Image processing and profile extraction

After extraction, each stack was processed separately with an in-house developed MATLAB code to crop the images only to the sections with the relevant information. A search algorithm first determined in a subset throughout the stack the preliminary centres of the two nominal cylinders visible in the images Figure 2a. Subsequently, the full stack was processed using the determined centres as start to find the actual centre in each image. In this way, a possible misalignment during the extraction of the stack could be eliminated and the images were cropped, leaving only the internal surface information alongside with the nominal internal cylinder plus a safety window of 70 pixel around the cylinder. The pixel outside the safety window were set to zero, to avoid additional information in the cropped stacks stemming from the external surface. Then, each image of the stack was transformed separately to polar coordinates and the safety window was removed, resulting in an image stack with the “rolled-out surface”, whereupon the nominal cylinder is now a straight horizontal line at the top of the image, accompanied by the surface variation in radial direction, Figure 2b. The start of the polar transformation is denoted by the vertical red line in Figure 2a and the red arrows in Figure 2a and 2b, thus the new coordinate origin is in the bottom left of each image. Subsequently, a search algorithm determined the pixel positions of each image containing the surface profile and stores the row number, i.e. radius for further processing. The scaling factors for each direction were calculated and applied prior to determining the mean as well as the Standard deviation (Std) for each angular position along the profile stack. In addition, the obtained profiles were re-scaled, such that the nominal channel radius is equal to the origin, with the convention that a smaller radial value shows as positive deviation from the nominal. Consequently, the mean deviation of the

surface to the nominal value can be represented as a simple height map scaled to the nominal channel value, cf. Figure 2c.

Figure 2. Image processing steps to obtain the mean surface profiles for each image stack. (a) Determination of the channel centre and selection of the ROI containing only the internal channel surface profile; (b) Polar transformation of the ROI, restacking and determination of the innermost surface pixel; (c) Resulting mean surface profile across the evaluated channel length; (d) Central algorithm blocks to obtain the mean profiles.

2.2.6. Profile characterization and analysis

The mean surface profiles were analysed regarding the properties of the most prominent peaks, such as maximum height and peak prominence, i.e. the height between the peak maximum and the closest valley to either side, the onset of the sag and dross-formation and the overall form deviation due to residual stresses during the build and after removal from the build platform.

To obtain the most prominent features, the shape of the profiles was approximated with a least squares spline, selecting knots with a spacing of 100 μm . In this way, the main shape is preserved, but high frequency components are suppressed. Subsequently, the actual peaks were determined in the raw surface profile and their properties such as height and prominence were extracted for evaluation.

A similar approach was applied determining the onset of the sag and dross formation. Here, the threshold was set to be the mean deviation, obtained from the bottom half of the profile (Figure 3 left and right section of the red vertical lines) plus the corresponding mean of the standard deviation at each sampling angle. Hence, the general surface variations stemming from laser-tracks or partially sintered and adhered particles of the as built surface do still contribute to the deviations within the sag and dross area, but their influence on the onset of this area was minimised. Subsequently, the deviation values in the unfiltered mean surface profile were determined which were closest to the obtained threshold value and the corresponding position was preserved. To achieve a more stable and symmetric thresholding, the position farther away from the ceiling centre, i.e. the position at 180°, of the channels was chosen as final threshold and mirrored around the ceiling centre (Figure 3, dashed vertical lines).

Figure 3. Exemplary mean surface profile with indications of the main evaluated features. The vertical dashed lines indicate the determined threshold for the onset of sag and dross defects. The red vertical lines indicate 90° and 270° with respect to the channel bottom centre, separating the top and bottom half of the cylinder. The small red arrows indicate the most prominent peaks of the profile. The secondary x-axis indicates the standard angular notation for LPBF.

Often, overall shape distortions in cylindrical LPBF parts result in an elliptical shape along the main channel axis. For this reason, a parametrised sinusoidal $y = a \cdot \sin(\omega \cdot x + \varphi) + d$ with x as independent and y as dependent variable, i.e. the profile value pairs, was fitted onto the mean profiles using a “least squares” approach, as the polar transformation of an ellipse is a sinusoidally shaped curve. Only the bottom half of the mean surface profiles i.e. the external regions in Figure 3 were used for the fitting, because the upper half of the channel has dominating contributions from sag and dross defects which would distort the fit. To obtain a good conversion of the fit, the mean value of the bottom half of the profile was determined and given as offset d , the difference between the mean profile value and the minimum profile value in the bottom half was given as amplitude a . The periodicity ω was set to be equal to $4\pi/360^\circ$, which is equivalent to the second harmonic of a

base sinus oscillation and the phase shift ϕ was set to $180^\circ/\pi$, i.e. a shift around 90 degree. As a final step, the necessary information was saved and exported in separate files.

3. Results and discussion

This section displays and evaluates the results obtained with the methodology introduced in the previous section. The novel approach is tested on the horizontal spyglass channels from 2 mm to 10 mm diameter. Based on the LPBF design guidelines in literature [15–17] the investigated range is prone to less critical form deviations, thus does normally not require internal supports and should allow a direct separation between form distortions and sag and dross formation. At first, basic results are introduced to establish a general evaluation of the demo part, whereas subsequently the analysis solely focuses on the results of the sag and dross defects evaluation for each channel's downfacing surface and the form distortions in the bottom areas of the channel.

3.1. Actual to nominal comparison

The overall “actual to nominal” comparison of the spyglass part is shown in Figure 4. The actual deviations of the determined surface by CT and the CAD are shown in a colour coded manner, whereupon negative deviations appear in blue colour and positive deviations appear in red. It is necessary to mention that CT artefacts can have an impact on the quality of the obtained surface and thus the analysis, however after thorough inspection of the scanned volume no artefacts could be found inside the analysed ROI. While looking at the outside of the 3D rendering of the part, large deviations can only be seen for the sections with larger channel diameters whilst there is only little deviation for channels up to 6 mm diameter.

Figure 4. 3D rendering of the fully reconstructed spyglass part with “actual-to-nominal” comparison. The deviations from the nominal model are shown in a colour coded fashion, and with a frequency distribution plot on the right. A part of the internal channel topography for the two top sections is displayed in the insets (a) and (b), revealing large sag and dross formations in the top centre area of the channel. The inset (c) shows the obtained Ra values for the external flat facets of the largest cylinder section.

However, when looking at the insets in Figure 4(a, b), displaying two sections of the internal surface of the 2 mm and 4 mm channels, it is obvious that large positive deviations are also present for channels with smaller diameters. When looking at the distribution of deviations, it might seem at first glance that the deviation from the nominal could be biased by a misalignment between the CAD and the determined surface of the volume. However visual inspection of the as-built part clearly revealed elliptical channels for diameters greater than 6 mm, which fits well with the obtained deviation distribution. The observation of the visual inspections is also investigated in more detail in a later section of this paper.

It is important to point out again that AM processes bear several different origins for part distortion and deviation which are in most cases interconnected and influence each other. For example, in the part at hand, the source for part deviations which becomes dominant in the sections with larger channel diameters starting from 8 mm onwards are caused by residual stresses induced during the build of the part resulting in warpage and shape distortions.

On the other hand, in channels with smaller diameters, sag and dross formation are the main driving factors for part deviations. Taking another look at the two internal surface topographies shown in the insets of Figure 4 one can clearly observe an angular dependency on the amount of deviation from the nominal. The largest deviations emerge always in the same angular areas, with large protrusions on the channel ceiling sides and smaller sagging in the ceiling centre, in fact suggesting a self-supporting behaviour in the centre region close to the top of the channel. However, the amount of information, which can be extrapolated from an “actual to nominal” comparison is strongly limited due to the enmeshment and high complexity of the various root causes yielding distortions in AM parts. Thus, the following sections rely on the extrapolated rolled-out raw data (Figure 3) for a refined evaluation of the source of deviations.

3.2. Evaluation of the overall shape distortions

The shape distortions of cylindrically shaped features in AM parts are often prone to become elliptical in shape instead of being circular due to residual stress during the build. Mathematically speaking, the polar transformation of an ellipse results in a sinusoidal curve thus sinusoids are fitted onto the obtained mean profiles to further investigate the overall form deviation. As an example, Figure 5 shows the mean profiles and the fitted sinusoids for the 2 mm (Figure 5, top left) and 10 mm (Figure 5, bottom left) diameter sections of the spyglass artefact, whereupon the surface points excluded from the fit are denoted in grey.

Figure 5. Mean profiles and sinusoidal fit for the bottom half of the channels with 2 mm and 10 mm diameter. The profile data used for the fit are pictured in blue, the points excluded from the fit are shown in grey and the fitted sinusoidal in red. The difference in amplitude and offset of the sinusoidal displays well the augmented form deviation for increasing channel diameter. The table on the right shows the best fit parameter for the different spyglass sections and the corresponding adjusted R² value.

In addition, the obtained parameters of the sinusoidal fits as well as the adjusted R^2 values of the fit are listed in the adjunct table of Figure 5 for all evaluated sections. In all cases the sinusoidal replicates the mean profile sections quite well, only the 4 mm channel shows a slightly reduced adjusted R^2 value as the channel bottom showed larger variations possibly caused by a small re-coating issue during the build. Moreover, the defect variations become more pronounced with respect to the channel diameter, as the length of the arc for a certain angle becomes shorter for smaller radii and thus the deviations are “accumulated” in a smaller area.

To be able to better quantify the amount of form deviation, the minimum and maximum deviations from the nominal radius are determined by subtraction or addition of the amplitude from the offset parameter, which correspond to the small and large axis of the ellipse in Cartesian coordinates. To better illustrate the changes in channel shape from a circle, Figure 6 shows the trend lines of the bottom section versus the polar angle from 0 to 90 degree once with their actual deviations, Figure 6a and once normalised to the respective channel radius (r), Figure 6b, using: deviation/(r/100). In particular, Figure 6b shows an asymptotic behaviour for the amount of deviation with respect to the channel radius and angle, indicating that the contribution of distortions due to residual stresses is strongly dependent on the channel radius and residual stresses are the dominant source of deviation for channel diameters > 6 mm. In contrast, the distortions in channels below a diameter of 6 mm are not predominantly caused by residual stresses, but by a combination of other sources of error, like sag and cross protrusions.

Figure 6. Amount of shape distortion in the cylinder bottom half versus the polar angle, for each of the inspected cylindrical sections. The graph in (a) shows the obtained surface points with corresponding trend lines of the actual deviation versus the polar angle; (b) displays the deviation normalised by the channel radius. For a channel diameter greater than 6 mm the deviation is less dependent on the radius but strongly dependent on the build angle.

The information in the adjunct table of Figure 5 can eventually be used to obtain a redesigned channel shape by intentionally biasing the initial design to reduce the general form deviations after build. To achieve this, the obtained sinusoidals along with the nominal diameter are used to determine the “new” pre-distorted channel shape by adding the sinusoidal’s offset to the nominal radius (dimensional compensation) and adding the sinusoidal to the sides of the channel while subtracting it from the top and bottom of the nominal diameter (compensation on circularity). The result is a slightly bigger and elliptically shaped channel as shown in Figure 7, right (orange dots). In comparison to the initial nominal circular section, the ellipse now has its major axis in vertical direction counteracting the residual stresses during the build. To get a better understanding of the as built mean channel shape, the image on the left of Figure 7 shows a “view” through the 2 mm channel section with the nominal channel denoted in red. Well visible are the sag and cross on the ceiling centre of the channel,

but also it can be noticed that the overall channel is slightly smaller and overbuild in the bottom up-facing surface, indeed resulting in an elliptical outline, whereupon the ellipses' major axis lies in horizontal direction.

Figure 7. Form deviation compensation demonstrated on the 2 mm spyglass section. The image on the left shows the average of the cross-sectional images along the 2 mm channel, accompanied by the nominal channel denoted in red. The graph on the right shows the nominal cylinder diameter (D_n , blue) along with the calculated form compensations, whereupon the yellow dots show the form compensation only applied on the bottom part (bot comp) and the orange dots the form compensation applied along the entire circumference (top/bot comp).

Notwithstanding, the proposed method only accounts for the form deviation in the lower half of the channels and in this approach it is assumed that the deviation is symmetrical with respect to the horizontal axis, as the actual form deviation in the upper part of the channels is hidden by superposition of sag and dross defects. For this reason, the graph on the right of Figure 7 shows the elliptical compensation applied throughout the full channel (orange dots), with A_E and B_E indicating the values of the major and minor axes of the calculated ellipse. In addition, another route of compensation is included (yellow dots), whereas the insets 1. and 2. enable a closer look onto the deviations of the two approaches.

In the latter compensation method, the form compensation is only applied in the bottom half of the channel, while only adding the offset (dimensional compensation) on the top half of the channel, yielding a semicircle with slightly larger radius and an elliptical bottom half (yellow dots). In this way, the form compensation is only applied where the form distortion can be well separated from other sources of error, and thus correctly quantified, whereas the compensation route for the top half of the channel could be a combination of the results derived from the sag and dross evaluation, which are discussed in the following section, and the calculated dimensional offset.

3.3. Characterization of sag and dross formation

The characterization of sag and dross effects in overhang regions is not trivial due to the fact that these effects are strongly material and process dependent and are the result of a highly complex mix of physical processes occurring during the build of AM parts. Here, the results obtained from the stacked raw profiles are displayed and discussed intensively.

At first, it is necessary to look in more detail at the distribution of the deviations across the channels, as the later determined mean surface profile, even when accompanied by its standard deviation, only shows the mere generalised behaviour along the investigated channel sections. Thus, Figure 8 displays the polar transformed profiles separately for each cross-section of channels 2, 6 and 10 mm in a 2.5D visualisation, whereupon the deviation from the nominal is shown additionally as a coloured map easing the understanding of the displayed content.

Figure 8. 2.5D representation of the internal line profiles obtained from the cross-sections over a length of 7.8 mm. The deviations from the nominal radius are shown on the z-axis and as coloured map. In (a, 2 mm) and (b, 6 mm) the main deviations are present in overhanging regions, around the ceiling centre, resulting in large sag and dross formations, (c, 10 mm) shows that deviations by shape distortions caused by residual stresses are influencing the entire channel circumference.

The profiles are plotted against the channel circumference in x direction and the y axis shows the profile cross-sectional position throughout the evaluated channel length of 7.8 mm. On first glance, it becomes again clear how the largest deviations and surface height variations always occur in the same areas, corresponding to the ceiling centre of the channels and up to a certain extent also in the bottom centre, while the variation in deviation stays quite constant on the sides of the channels. This is in perfect agreement with the literature as it is

common knowledge that the LPBF process can build up parts with limited protrusions defects in downfacing areas if a certain overhang angle with respect to the build direction is not surpassed [15–17]. When examining the different profiles with respect to their general deviation from the nominal, a strong trend from smaller to larger channel diameters emerges caused by the change in the root cause for deviations i.e. from mainly sag and dross defects to overall shape deformation. For example, a comparison between the 2 mm and 10 mm diameters, cf. Figure 8a and 8c, shows that, while the deviation range is the same, the small channel with 2 mm diameter has the deviations concentrated in the upper half of the channel - in fact within 0-60° downfacing angle (in LPBF notation) - whilst the deviations for the larger channel with 10 mm diameter are more spread out across the whole circumference. The change in the dominance of the drivers for the deviations becomes clear comparing the extreme cases to the intermediate state, channel diameter of 6 mm, and observing how the weights of error contributors are getting interchanged while increasing/decreasing diameter size.

To get a better understanding of the general behaviour throughout the evaluated channel lengths, Figure 9 shows the calculated mean surface profiles with corresponding standard deviation (grey overlay) and the determined sag and dross onset thresholds (dotted vertical lines) on the left. For more clarity, the sag/dross onset angle, the standard deviation values for the maximum peak deviation and the Std at 90°, i.e. the channel side, are shown in the adjunct table on the right. The profiles are plotted against the angle, whereupon the calculated ceiling centre is at 180° (0° downfacing in LPBF notation). The determined onset angles remain almost constant, besides a small increase towards smaller channels (68.6° for 2 mm channel), cf. table on the right of Figure 9.

Figure 9. Mean surface profiles of the different spyglass sections. The stacked view shows the change in sag and dross formation on the top centre of the channels between the dashed lines. The variation for each particular angular direction is denoted by the grey overlay, which is the corresponding standard deviation. The table on the right shows some quantitative values extracted from the presented profiles.

Apart from statistical deviations, the dross formations show a strong symmetrical behaviour with respect to the ceiling centres, i.e. the mean deviations on left and right channel ceiling show only marginal differences, for all

evaluated channels regardless of the channel diameter, demonstrating and confirming the strong angular dependency of sag and dross defects.

Moreover, the stacked profiles also reveal the standard deviation dependency with respect to the angle, cf. Figure 9 denoted by the variation of the grey overlay. Whenever the deviations increase, regardless of the root mean cause and channel diameter, the standard deviation rapidly increases in these areas. For example, the standard deviation on the sides of the channels is low ($\approx 8.6 \mu\text{m}$) and in good agreement with the measured lower surface roughness on the sides of the spyglass benchmark compared to inclined or horizontal surfaces, cf. inset (c) on the bottom left of Figure 4 for the R_a roughness values. Naturally, the standard deviation is not equivalent to the roughness of a surface, but shows that the surface variations inside channels are also strongly dependent on the angle of inclination although the surface roughness and variations themselves are, partially, caused by different physical phenomena, e.g. for internal features roughness might be driven by local heat accumulation. To underline this dependency on the angle, the two extrema of the standard deviation are displayed in the adjunct table of Figure 9. The standard deviation at the maximum deviation of the profiles is an order of magnitude higher compared to the areas which show the smallest deviations, i.e. the sides of the channel built under an angle approaching the 90° in LPBF notation (namely vertical direction or building direction).

Another important observation is the behaviour of the surface in the very centre of the ceiling in which the sag peak appears between the two symmetrical main dross peaks. Here, the last powder-layer is deposited and processed by the laser closing the channel, which creates a small peak close to a single layer height and visible in all profiles, as underlying powder-layers are also partially re-melted. This smaller sagging is favoured thanks to the layers right before the top layer having already more solidified material induced by dross built-up in previous layers, thus becoming self-supporting which is the reason why the deviations between the two peaks rapidly decreases until the ceiling centre. This sort of behaviour of sag and dross is not common and particularly depending on the material and parameters used to manufacture the spyglass. A more in depths analysis of the different peaks is given later in this section.

As discussed in section 3.2 the overall form deviation of the channels strongly increases from smaller to larger channels. As a result, the sag and dross areas are “sagging” into the overall form deviations, while the dross peaks become less pronounced for larger channels and almost disappear for the 10 mm channel c.f. Figure 9. For this reason, the self-supporting behaviour combined with the form deformation “lifts” the sag area at the ceiling centre back or even above the nominal cylinder value, giving a misperceived correlation between the defect size and the channel diameter. The last section of this paper tackles the latter issue with the implementation of a peak analysis on the mean surface profiles.

Besides 3D plots and a clear definition of the onset angle for sag and dross, another important aspect to take into account while studying the defects of channels is the position, total height and prominence of major peak deviations. This determines first, possible insights on the dependency of these characteristics on the channel diameter (or on LPBF parameters settings, if desired), and second, a general overall description of the sag and dross extension that can be used as initial input to later on generate an a-priori correction of the channel geometry.

The novel characterization approach of this work makes it straightforward to determine the local maxima and minima (peaks) of the channel profile, since it works on the rolled-out surface after polar transformation. For this reason, a simple local peak discovery algorithm can be implemented to perform this analysis quickly and automatically for each channel. Although a peak analysis might seem redundant, the following section demonstrates that, if properly applied, peak analysis and the extrapolation of peak characteristics, as their prominence, can further cast light on the complexity of sag and dross, and aid the general understanding of these defects.

While defining the peak analysis algorithm, special care must be taken on the initialization of a minimum peak prominence [43] value. The prominence of a peak measures how much the peak stands out due to its intrinsic height and its location relative to other peaks. Even if the analysis is carried out on the approximated least squares spline, minor peaks due to the high surface irregularities of the downfacing region could still be detected (Figure 9). Instead, to capture only the peaks that describes the global shape of the defects, a minimum prominence value is determined that successfully filters out the minor deviations (as sketched in Figure 2). Subsequently, the actual values of the peaks' characteristics are retrieved from the average raw profiles. Those values are summarized in Figure 10, for the investigated spyglass sections.

Figure 10. Peak analysis of the spyglass benchmark part; max peaks' height and prominence results plus tabulated peak angle positions for sag, dross, and local minima i.e. the angle position with the least deviation from the nominal (all in LPBF notation).

When looking at the maximum height of the dross formation for the different channels, no major difference is noticeable if the standard deviation is taken into account. However, with the prominence values, it becomes clear how the dross formation rises slowly going towards smaller channels, due to the higher heat accumulation and minor deformation. On the other hand, the sag in the centre of the downfacing area seems to have different values depending on the diameter. As discussed previously, the sag defect is due to the fact that the last layers, while closing the channel, find already a dross structure to use as supports and this limits the protrusion formation on the loose powder beneath. Hence, the sagging should be constant and on the order of magnitude of the employed layer thickness. This is again confirmed if the prominence values of the sagging peaks are investigated, obtaining an average protrusion value of $\sim 30 \mu\text{m}$.

Regarding the peaks angular position relative to the downfacing angle, the behaviour seems consistent for both local maxima and minima, with the position of the peaks being mostly independent of the channel diameter. For this test part, dross peaks are positioned at around 17° downfacing angle (LPBF notation) and the sag peak is, as expected, positioned at the centre of the downfacing area. As for the dross onset angle, the only major deviation related to the dross peak position is for the 2 mm channel, where the dross peak angle moves at a 21° angle, again probably due to the higher amount of dross formation that smaller LPBF channels experience. The local minima analysis can be used as well to determine the onset and extension of the sag defect inside the channels (around 8° downfacing angle onset for the spyglass) and the overall local minima position. As mentioned in section 3.2, the local minima show that for the spyglass channels the smallest deviation from the nominal is always located on the sides of the channel, approaching the 90° angle on either channel side.

4. Conclusion and outlook

In this work, a novel tomographic based geometrical evaluation approach is presented for the characterization of defects and deviations of internal circular channels produced by LPBF. The approach was based on accurately planned X-ray CT acquisitions, to obtain high resolution 3D datasets of LPBF fabricated channels with different diameters from the “spyglass” benchmark, a purposely designed artefact. The resulting image-stack of the 3D object were processed with an algorithm developed to derive polar-transformed mean profiles of the scanned channels, enabling a derivation of both qualitative estimations (e.g. 2.5D profile plots) and quantitative descriptors of the internal channel surface. More specifically, the purpose of the subsequent algorithm’s analysis step was to output both, the general form deviation due to residual stresses built up during LPBF manufacturing, as well as a list of specific descriptors for sag and dross defects, comprising sag/dross onset angles, maximum and minimum dross extension and prominence and their associated standard deviations.

As first showcase, quantitative results, which have been acquired on a fabricated AlSi7Mg0.6 benchmark with horizontally printed channels, demonstrate the viability of the suggested approach. The proposed correction route of the general form deviation, based on best-fit sinusoidals on the unwrapped mean surface profile, permits to compute an elliptically deformed channel for a-priori shape-compensation. However, the compensation is quantitatively valid only for the bottom part of the investigated channels, as the top half is influenced strongly by the superimposition of general form deviation and sag/dross protrusions.

Concerning the obtained descriptors of sag and dross defects, the results show that the onset angle of the dross protrusion for AlSi7Mg0.6 is stable at a downfacing angle of $61.9 \pm 4.5^\circ$ around the ceiling centre (LPBF notation), whereupon the angle slightly increases for smaller channels. However, the obtained values are only valid for the case of this study and are prone to vary on a different LPBF machine and/or material. Furthermore, it is demonstrated how the evolution of sag and dross, in dependence of variables like channel dimension, can be obtained, thanks to the combination of the general analysis of the mean profiles of the channels plus an in-depth peak analysis.

Peculiarly, an unusual behaviour is observed for the downfacing surface of the fabricated benchmark, as the dross build-up of the layers before the ceiling centre behaves as a supporting structure for the last scanned layer closing the channel, thus presenting only a small sag peak protrusion from 8° to 0° downfacing angle. The central sag peak is mostly independent of the channel diameter, and is in the order of magnitude of the utilized LPBF layer thickness of $30\text{ }\mu\text{m}$, as the prominence data from the peak analysis unravel.

The presented methods and analysis strategies show a first important step towards an a-priori compensation during the design stage. For the future, this approach will be further developed to obtain a full compensation suggestion of the entire channel circumference, integrating the descriptors of sag and dross in a compensation model. Combined with the general form correction, this compensation strategy can be a useful tool for industrial sectors in which the channel shape cannot be altered.

Furthermore, this approach offers potential as experimental data are normally easier to handle than complex multi-physics simulations and offer in general lower lead times. On the other hand, the experimental results from this tomographic characterisation route can possibly aid multi-physics simulations of LPBF sag and dross formation [37,38], to perform validation or tuning of the employed simulation model. In addition, the derived sag and dross characteristics could also be a useful instrument to further refine LPBF design guidelines, e.g. to more precisely define the onset angle for which supports should be added depending on material and processing parameters.

Finally, the approach can also easily be extended for general metal and non-metal AM channels, to obtain standard surface texture parameters (e.g. R_a , S_a) with common available software as the unwrapping of the surface preserves the topography and thus yields similar surface maps comparable to areal instruments with the strong benefit of being applicable on internal channel surfaces.

Acknowledgements

This research was funded by the EU Framework Programme for Research and Innovation - Horizon 2020 - Grant Agreement No 721383 within the PAM² (Precision Additive Metal Manufacturing) research project. Umberto Paggi and Lore Thijs (3D Systems) are kindly acknowledged for the fabrication of the spyglass benchmark at the 3D Systems Leuven facilities.

References

- [1] T.T. Wohlers, Wohlers report 2019: 3D printing and additive manufacturing state of the industry, 2019.
- [2] T.D. Ngo, A. Kashani, G. Imbalzano, K.T.Q. Nguyen, D. Hui, Additive manufacturing (3D printing): A review of materials, methods, applications and challenges, *Compos. Part B Eng.* 143 (2018) 172–196. <https://doi.org/10.1016/j.compositesb.2018.02.012>.
- [3] P.K. Gokuldoss, S. Kolla, J. Eckert, Additive Manufacturing Processes: Selective Laser Melting, Electron Beam Melting and Binder Jetting—Selection Guidelines, *Materials*. 10 (2017) 672. <https://doi.org/10.3390/ma10060672>.
- [4] A. Gisario, M. Kazarian, F. Martina, M. Mehrpouya, Metal additive manufacturing in the commercial aviation industry: A review, *J. Manuf. Syst.* 53 (2019) 124–149. <https://doi.org/10.1016/j.jmsy.2019.08.005>.
- [5] S. Vock, B. Klöden, A. Kirchner, T. Weißgärber, B. Kieback, Powders for powder bed fusion: a review, *Prog. Addit. Manuf.* 4 (2019) 383–397. <https://doi.org/10.1007/s40964-019-00078-6>.
- [6] T. DebRoy, T. Mukherjee, J.O. Milewski, J.W. Elmer, B. Ribic, J.J. Blecher, W. Zhang, Scientific, technological and economic issues in metal printing and their solutions, *Nat. Mater.* 18 (2019) 1026–1032. <https://doi.org/10.1038/s41563-019-0408-2>.
- [7] M. Seifi, M. Gorelik, J. Waller, N. Hrabe, N. Shamsaei, S. Daniewicz, J.J. Lewandowski, Progress Towards Metal Additive Manufacturing Standardization to Support Qualification and Certification, *JOM*. 69 (2017) 439–455. <https://doi.org/10.1007/s11837-017-2265-2>.
- [8] P. Charalampous, I. Kostavelis, D. Tzovaras, Non-destructive quality control methods in additive manufacturing: a survey, *Rapid Prototyp. J.* 26 (2020) 777–790. <https://doi.org/10.1108/RPJ-08-2019-0224>.
- [9] R.K. Leach, D. Bourell, S. Carmignato, A. Donmez, N. Senin, W. Dewulf, Geometrical metrology for metal additive manufacturing, *CIRP Ann.* 68 (2019) 677–700. <https://doi.org/10.1016/j.cirp.2019.05.004>.
- [10] S. Carmignato, W. Dewulf, R. Leach, eds., *Industrial X-Ray Computed Tomography*, Springer International Publishing, Cham, 2018. <https://doi.org/10.1007/978-3-319-59573-3>.
- [11] A. Khorasani, I. Gibson, J.K. Veetil, A.H. Ghasemi, A review of technological improvements in laser-based powder bed fusion of metal printers, *Int. J. Adv. Manuf. Technol.* 108 (2020) 191–209. <https://doi.org/10.1007/s00170-020-05361-3>.
- [12] R. Leach, S. Carmignato, *Precision Metal Additive Manufacturing*, 1st ed., CRC Press, First edition. | Boca Raton, FL : CRC Press, 2020., 2020. <https://doi.org/10.1201/9780429436543>.
- [13] J.L. Bartlett, X. Li, An overview of residual stresses in metal powder bed fusion, *Addit. Manuf.* 27 (2019) 131–149. <https://doi.org/10.1016/j.addma.2019.02.020>.
- [14] A. Charles, A. Elkaseer, L. Thijs, V. Hagenmeyer, S. Scholz, Effect of Process Parameters on the Generated Surface Roughness of Down-Facing Surfaces in Selective Laser Melting, *Appl. Sci.* 9 (2019) 1256. <https://doi.org/10.3390/app9061256>.
- [15] D. Thomas, The Development of Design Rules for Selective Laser Melting, PhD Thesis, University of Wales, 2009. <https://repository.cardiffmet.ac.uk/handle/10369/913> (accessed November 19, 2017).
- [16] O. Diegel, A. Nordin, D. Motte, *A Practical Guide to Design for Additive Manufacturing*, Springer Singapore, Singapore, 2019. <https://doi.org/10.1007/978-981-13-8281-9>.
- [17] C. Emmelmann, D. Herzog, J. Kranz, Design for laser additive manufacturing, in: *Laser Addit. Manuf.*, Elsevier, 2017: pp. 259–279. <https://linkinghub.elsevier.com/retrieve/pii/B9780081004333000105> (accessed October 3, 2019).
- [18] A. Charles, A. Elkaseer, L. Thijs, S.G. Scholz, Dimensional Errors Due to Overhanging Features in Laser Powder Bed Fusion Parts Made of Ti-6Al-4V, *Appl. Sci.* 10 (2020) 2416. <https://doi.org/10.3390/app10072416>.
- [19] M.S. Shinde, K.M. Ashtankar, Additive manufacturing–assisted conformal cooling channels in mold manufacturing processes, *Adv. Mech. Eng.* 9 (2017) 168781401769976. <https://doi.org/10.1177/1687814017699764>.

- [20] Mandanà Moshiri, Integrated process chain for first-time-right mould components production using laser powder bed fusion metal additive manufacturing, PhD Thesis, DTU, 2020. <http://rgdoi.net/10.13140/RG.2.2.17942.98880> (accessed June 29, 2020).
- [21] R. Mertens, S. Clijsters, K. Kempen, J.-P. Kruth, Optimization of Scan Strategies in Selective Laser Melting of Aluminum Parts With Downfacing Areas, *J. Manuf. Sci. Eng.* 136 (2014) 061012. <https://doi.org/10.1115/1.4028620>.
- [22] H.L. Wei, T. Mukherjee, W. Zhang, J.S. Zuback, G.L. Knapp, A. De, T. DebRoy, Mechanistic models for additive manufacturing of metallic components, *Prog. Mater. Sci.* (2020) 100703. <https://doi.org/10.1016/j.pmatsci.2020.100703>.
- [23] K. Kempen, F. Welkenhuyzen, J. Qian, J.-P. Kruth, Dimensional accuracy of internal channels in SLM produced parts, in: 2014 ASPE Spring Top. Meet. Dimens. Accuracy Surf. Finish Addit. Manuf. Berkeley CA Apr, 2014: pp. 13–16. <https://lirias.kuleuven.be/handle/123456789/446640>.
- [24] J.C. Snyder, C.K. Stimpson, K.A. Thole, D.J. Mongillo, Build Direction Effects on Microchannel Tolerance and Surface Roughness, *J. Mech. Des.* 137 (2015) 111411. <https://doi.org/10.1115/1.4031071>.
- [25] J.C. Snyder, C.K. Stimpson, K.A. Thole, D. Mongillo, Build Direction Effects on Additively Manufactured Channels, *J. Turbomach.* 138 (2016) 051006. <https://doi.org/10.1115/1.4032168>.
- [26] A. Thompson, I. Maskery, R. Leach, Internal surface measurement by X-ray computed tomography: an additive manufacturing industrial case study, in: *Proc. 3rd Dimens. X-Ray Comput. Tomogr. Conf. DXCT 2018*, 2018. <https://nottingham-repository.worktribe.com/output/944634>.
- [27] A. Thompson, L. Körner, N. Senin, S. Lawes, I. Maskery, R.K. Leach, Measurement of internal surfaces of additively manufactured parts by X-ray computed tomography, in: *Proc. 7th Conf. Ind. Comput. Tomogr. ICT 2017*, Leuven (BE), 2017. <https://nottingham-repository.worktribe.com/output/847081/measurement-of-internal-surfaces-of-additively-manufactured-parts-by-x-ray-computed-tomography>.
- [28] A. Townsend, L. Pagani, P. Scott, L. Blunt, Areal surface texture data extraction from X-ray computed tomography reconstructions of metal additively manufactured parts, *Precis. Eng.* 48 (2017) 254–264. <https://doi.org/10.1016/j.precisioneng.2016.12.008>.
- [29] F. Zanini, L. Pagani, E. Savio, S. Carmignato, Characterisation of additively manufactured metal surfaces by means of X-ray computed tomography and generalised surface texture parameters, *CIRP Ann.* 68 (2019) 515–518. <https://doi.org/10.1016/j.cirp.2019.04.074>.
- [30] C.G. Klingaa, T. Dahmen, S. Baier, S. Mohanty, J.H. Hattel, X-ray CT and image analysis methodology for local roughness characterization in cooling channels made by metal additive manufacturing, *Addit. Manuf.* (2020) 101032. <https://doi.org/10.1016/j.addma.2019.101032>.
- [31] C.G. Klingaa, M.K. Bjerre, S. Baier, L.D. Chiffre, S. Mohanty, J.H. Hattel, Roughness Investigation of SLM Manufactured Conformal Cooling Channels Using X-ray Computed Tomography, in: *Proc. 9th Conf. Ind. Comput. Tomogr. Padova Italy ICT 2019*, 2019. <https://orbit.dtu.dk/en/publications/roughness-investigation-of-slm-manufactured-conformal-cooling-cha>.
- [32] J. Pakkanen, F. Calignano, F. Trevisan, M. Lorusso, E.P. Ambrosio, D. Manfredi, P. Fino, Study of Internal Channel Surface Roughnesses Manufactured by Selective Laser Melting in Aluminum and Titanium Alloys, *Metall. Mater. Trans. A.* 47 (2016) 3837–3844. <https://doi.org/10.1007/s11661-016-3478-7>.
- [33] M. Ghobadi, Y.S. Muzychka, A Review of Heat Transfer and Pressure Drop Correlations for Laminar Flow in Curved Circular Ducts, *Heat Transf. Eng.* 37 (2016) 815–839. <https://doi.org/10.1080/01457632.2015.1089735>.
- [34] S. Sandron, B. Heery, V. Gupta, D.A. Collins, E.P. Nesterenko, P.N. Nesterenko, M. Talebi, S. Beirne, F. Thompson, G.G. Wallace, D. Brabazon, F. Regan, B. Paull, 3D printed metal columns for capillary liquid chromatography, *The Analyst.* 139 (2014) 6343–6347. <https://doi.org/10.1039/C4AN01476F>.
- [35] A.M. Kamat, Y. Pei, An analytical method to predict and compensate for residual stress-induced deformation in overhanging regions of internal channels fabricated using powder bed fusion, *Addit. Manuf.* 29 (2019) 100796. <https://doi.org/10.1016/j.addma.2019.100796>.
- [36] U. Paggi, M. Sinico, L. Thijs, W. Dewulf, B. Van Hooreweder, Improving the dimensional accuracy of downfacing surfaces of additively manufactured parts, in: *Proc. Spec. Interest Group Meet. Adv. Precis. Addit. Manuf.*, euspen, 2019: pp. 35–38. <https://lirias.kuleuven.be/retrieve/547113>.
- [37] H.M. Khan, M.H. Dirikolu, E. Koç, Parameters optimization for horizontally built circular profiles: Numerical and experimental investigation, *Optik.* 174 (2018) 521–529. <https://doi.org/10.1016/j.jilleo.2018.08.095>.
- [38] Y. Solyaev, L. Rabinskiy, D. Tokmakov, Overmelting and closing of thin horizontal channels in AlSi10Mg samples obtained by selective laser melting, *Addit. Manuf.* 30 (2019) 100847. <https://doi.org/10.1016/j.addma.2019.100847>.

- [39] E. ISO, 4287—Geometrical Product Specifications (GPS)—Surface Texture: Profile Method—Terms, Definitions and Surface Texture Parameters, Int. Organ. Stand. Geneva Switz. (1997).
- [40] E. ISO, 4288—Geometrical product specifications (GPS)—surface texture: profile method—rules and procedures for the assessment of surface texture, Int. Organ. Stand. Geneva Switz. (1996).
- [41] H. Villarraga-Gómez, S.T. Smith, Effect of the number of projections on dimensional measurements with X-ray computed tomography, *Precis. Eng.* 66 (2020) 445–456. <https://doi.org/10.1016/j.precisioneng.2020.08.006>.
- [42] M. Sinico, E. Ametova, A. Witvrouw, W. Dewulf, Characterization of AM Metal Powder with an Industrial Microfocus CT: Potential and Limitations, in: *Proc. 2018 Summer Top. Meet. Adv. Precis. Addit. Manuf.*, American Society for Precision Engineering, 2018: pp. 286–291. <https://lirias.kuleuven.be/retrieve/514198>.
- [43] Prominence - MATLAB & Simulink - MathWorks Benelux, (2020). <https://nl.mathworks.com/help/signal/ug/prominence.html> (accessed July 7, 2020).

Journal Pre-proof