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Build orientation effects on the roughness of SLM channels

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Abstract

Increasingly advanced shapes and geometries are being manufactured using additive manufacturing and new characterization techniques must emerge in order to fully utilize the new possibilities given by freeform design. Cooling channels produced by the laser powder bed fusion process has been shown to have high roughness at overhanging areas due to powder particles being fused with the internal surface. Classic techniques for characterizing profile roughness are falling short with respect to internal surfaces in freeform geometries. Hence, this work presents a methodology for characterizing internal surface roughness by extracting roughness profiles through the use of image analysis and X-ray CT. In order to fully describe the internal surface roughness, two orientations were defined, namely the global and local orientations α and β . The internal profile roughness was evaluated in accordance with ISO 4287:1997. Seven selective laser melting manufactured straight channels made in 17-4 PH stainless steel were CT scanned and analyzed with the proposed methodology. Results showed that the Ra-values inside the channel were dependent on both α and β . The average Ra-values and their standard deviations were found to be decreasing rapidly with increasing α . The highest average roughness was found for $\alpha = 0^\circ$, where an average Ra-value of $70.7 \mu\text{m}$ was found. The lowest average roughness was found at $\alpha = 90^\circ$, where an average Ra-value of $6.7 \mu\text{m}$ was found. Furthermore, it was found that the surface texture and roughness changed dependent on the location along the length of the channel produced at $\alpha = 0^\circ$. These findings suggest the importance of characterizing the internal surface roughness of cooling channels with respect to both the global build orientation of a channel, the local orientation within a channel and the specific location along the length of a channel.

SLM, powder bed fusion, additive manufacturing, cooling channels, X-ray CT, roughness analysis

1. Introduction

Metal additively manufactured channels in combination with freeform design are currently a rapidly expanding area within the design of additively manufactured injection and cooling systems. The advantages of conformal cooling channels over conventional cooling channels have been known for some time [1–3], but the application is recently developing due to the current advances within additive manufacturing (AM). The cooling capability of channels is determined by the actual geometry of the channel, the area of the channel wall and the internal surface texture. It has been shown in literature that metal additively manufactured components are experiencing high roughness at overhanging areas. This roughness may influence the cooling properties of the channels by affecting the flow in the channels and increasing the fluid to wall contact area. The complex geometries of conformal channels may be difficult to characterize properly using conventional metrological techniques such as profilometers. Therefore, X-ray CT is increasingly utilized for characterizing additively manufactured components due to its capability of looking inside complex geometries and shapes.

The roughness on overhanging areas of selective laser melting (SLM) components has been shown to be dependent on the angling of the surface with respect to the build plate [4–6]. Much research has been dedicated to investigating the influence of process parameters on the roughness at overhanging areas, but this does not enable full characterization of the internal surface roughness of the components.

This work seeks to characterize the internal surface texture of cooling channels manufactured by the SLM process at different global orientations (α) and local orientations (β). First, a description of the methods and materials is given together with a brief description of the proposed methodology developed for generating profile roughness measurements from X-ray CT data. Second, the results will be shown and discussed with a focus on calculated Ra-values with respect to the global orientation α and the local orientation β and how the roughness is dependent on the location in the channel through the length. Finally, a conclusion is given together with suggestions for future work.

2. Methods and materials

In this section, the components investigated in this work is presented together with the procedure used for generating X-ray CT data. Finally, a brief description of a proposed methodology used for generating profile roughness measurements from X-Ray CT data is given.

2.1. Investigated components

The components investigated in this work consisted of seven cuboids made in 17-PH stainless steel. The cuboids had the dimensions $10 \text{ mm} \times 10 \text{ mm} \times 12.5 \text{ mm}$ (length, width, height) and are shown in Figure 1. The cuboids were manufactured with internal straight channels of different inclinations, namely: 0° , 15° , 30° , 45° , 60° , 75° and 90° . The channel diameter was $D = 2 \text{ mm}$ for all components. The components were part of a larger build job and were manufactured on an EOS M 290 system using process parameters as shown in Table 1.



Figure 1. Investigated components. Seven cuboids with internal channels at inclinations: 0°, 15°, 30°, 45°, 60°, 75° and 90°.

Table 1. Process parameters for the build job.

Process parameter	Value
Laser power, P_L	220.1 W
Layer height, Δz_{layer}	40 μm
Hatch spacing, Δy_{hatch}	110 μm
Scanning speed, v_{scan}	755.5 mm/s
Particle size	D50: 36-44 μm
Spot diameter, d_{spot}	100 μm

2.2. X-Ray CT and image processing

The X-ray CT scans were conducted using a Nikon XT H 225 ST system with a cone beam setup and a flat panel detector. Each component was scanned once with the same optimized scanning parameters. The X-ray tomograms were obtained using a W filament, a voltage of 220 kV, a power of 29.9 W, and a 0.5 mm Sn filter. Each of the 1571 projections was acquired using an exposure time of $t = 1$ s and two frames were averaged per projection. A voxel size of 15.9 μm was obtained with two by two binning. The cone beam reconstruction was conducted with the X-Tek CT Pro 3D software using filtered-back projection (Nikon Metrology Inc.).

The acquired and reconstructed volumes were subsequently realigned and cropped in Avizo 9.2 after which each volume was exported as a stack of 500 cross-sectional images along the direction of the channel. A stack represented a length of $500 \times 15.9 \mu\text{m} = 7.95$ mm in the middle of each channel. Each image stack was used as input for nominal/actual deviation analysis.

2.3. Method of analysis

In order to fully characterize the internal surface roughness of channels produced with different inclinations, two orientations were defined. Figure 2 shows the definition of the global and the local orientations, α and β respectively. α is the orientation of the length of a channel with respect to the build direction. β is the local orientation within a channel. With these orientations, it was possible to determine the effect of both the global orientation and the local orientation on profile roughness inside a channel.

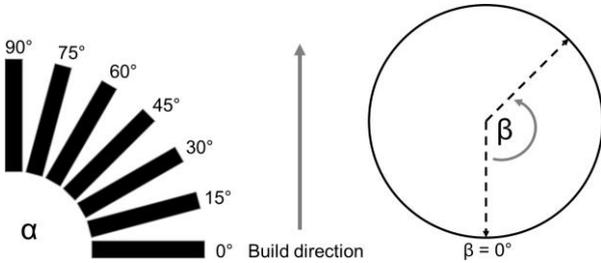


Figure 2. Definitions of the global orientation α and the local orientation β .

The procedure used for obtaining profile roughness measurements was based on a methodology introduced by Klingaa et. al (7). The methodology and related in-house Python code were expanded from their original design such that 3D deviation data was used to generate profile roughness measurements at 360° around a channel (8). The methodology has been sketched in Figure 3.

The method is based on segmenting aligned cross-sections of a reconstructed volume obtained from the X-ray CT procedure and subsequently load the images into an in-house Python code together with the corresponding segmentation value. The Python code then proceeds to generate a nominal surface to which the actual reconstructed surface is compared. This yields 3D deviation results that are subsequently used for extracting profile measurements along the length of a channel. The procedure of the analysis was repeated for all seven channels.

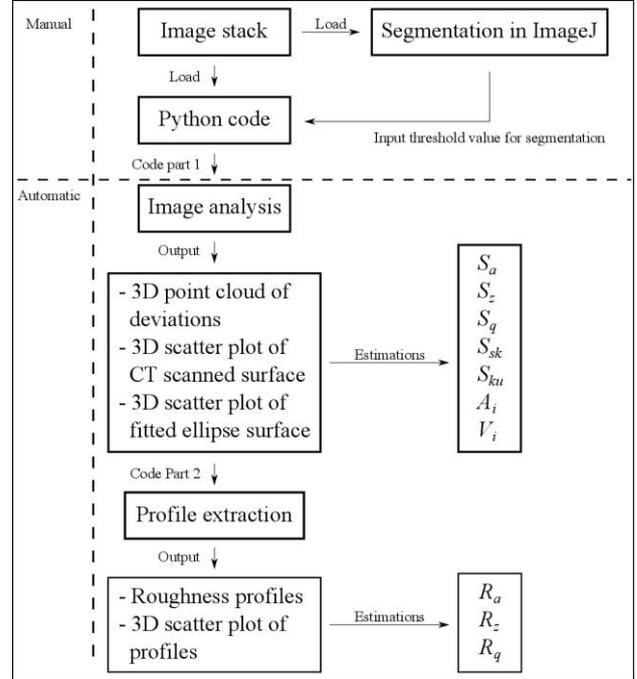


Figure 3. Methodology for generating profile roughness measurements of SLM manufactured cooling channels.

Figure 4 shows, as an example, the 3D scatter plot of the deviation analysis conducted for the channel produced at $\alpha = 30^\circ$ together with the corresponding extracted profiles. A single profile from Figure 4(b) is shown in Figure 5.

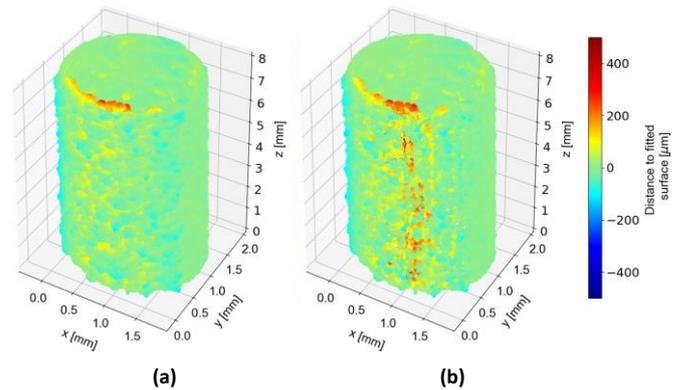


Figure 4. (a) Deviation analysis, output from code part 1 in Figure 3. (b) Extracted profiles, output from code part 2 in Figure 3.

The local orientation of the extracted profile was $\beta = 269.8^\circ$. As seen from the figure, the profile looks similar to a classic profile measurement. Each of the profiles was then subsequently used for calculating the arithmetical mean average height of the profile according to ISO 4287:1997 (9):

$$R_a = \frac{1}{l} \int_0^l |Z(x)| dx \quad (1)$$

where l is the total sampling length and $Z(x)$ is the height value at each point along the length. The roughness investigation in this work was viewed from a functionality standpoint. Thus, the evaluation length and sampling lengths according to the ISO standard were not considered specifically. Instead, each profile was used in its whole length to calculate the corresponding R_a -value of that profile. In order to ensure comparability between the separate profiles, each profile was leveled using a least squares fitting line.

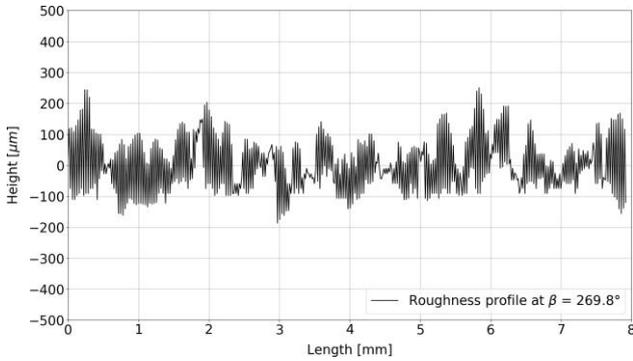


Figure 5. Extracted profile from analysed channel with global orientation $\alpha = 30^\circ$. The local orientation of the profile was $\beta = 269.8^\circ$.

3. Results and discussion

In this section, the results obtained by analyzing the seven channels will be discussed. Starting with the general influence of the defined orientations α and β , followed by the influence of the location along the length of the channel, shown with the channel produced at $\alpha = 0^\circ$ as an example.

3.1. Influence of the global orientation α and the local orientation β on R_a -values

Figure 6 shows the average R_a -values of each of the investigated channels together with the corresponding standard deviations. The R_a values are a function of the global build orientation α , also denoted $R_a(\alpha)$. The highest average R_a -value and the corresponding standard deviation is found at $\alpha = 0^\circ$. The magnitude of the average R_a -values and their standard deviations are decreasing with increasing α . This is likely due to

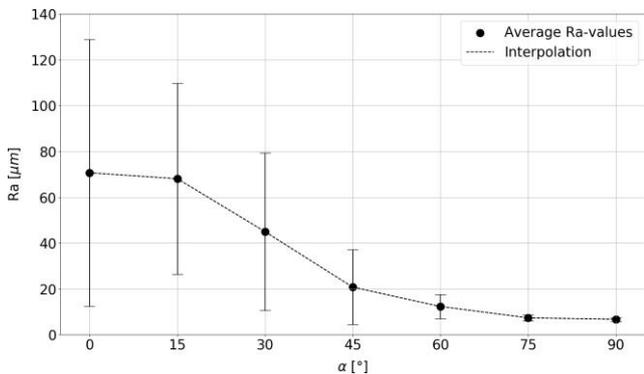


Figure 6. Average R_a -values as a function of the global orientation α .

the orientation dependent nature of roughness obtained with the SLM method. As indicated by Figure 4, the deviations observed are different dependent on the local orientation of the channel. The results from Figure 6 suggests that the influence from the local orientation is reducing with increasing α , resulting in a lower standard deviation at higher α -values. This can be further illustrated by considering Figure 7 and Figure 8, where polar plots of the R_a -values for the channels produced at $\alpha = 0^\circ$

and $\alpha = 90^\circ$ are shown as a function of β . The polar plot for $\alpha = 0^\circ$ was aligned such that $\beta = 0^\circ$ at the upward facing surface of the channel and $\beta = 180^\circ$ at the downward facing surface.

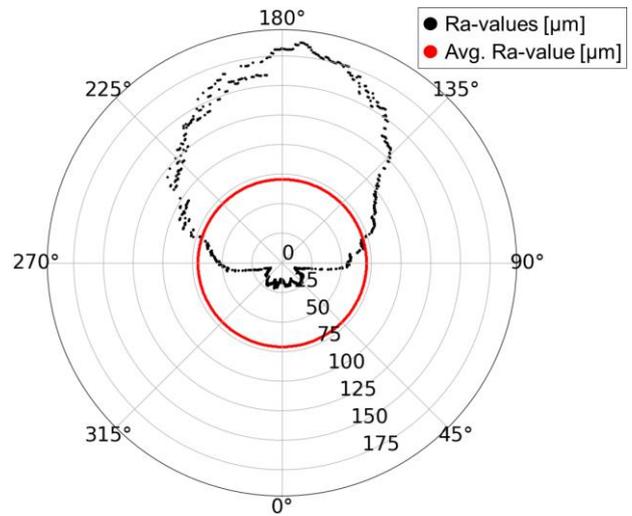


Figure 7. R_a -values as a function of the local orientation β for $\alpha = 0^\circ$.

Figure 7 shows how the local orientation is heavily influencing the calculated R_a -values. The roughness is rapidly increasing when β goes from 270° towards 180° or when β goes from 90° towards 180° . Furthermore, it can be observed how the roughness observed at the downward facing area, i.e. around $\beta = 180^\circ$, is the highest. This is not the case for the channel produced at $\alpha = 90^\circ$. Figure 8 shows that the R_a -values are more or less evenly distributed around the mean line, indicating that the local orientation has no influence when the channel direction is parallel to the build direction. This further suggests that the large standard deviations observed in Figure 6, at especially low α -values, are direct effects of the dependency on β . The small difference observed in Figure 6 between $\alpha = 75^\circ$ and $\alpha = 90^\circ$ is thought to be related to the voxel size obtained with the CT data used in the current study. As seen from Figure 6, the average R_a -values was calculated to be in the range of 6-8 μm for both orientations, as can also be seen for $\alpha = 0^\circ$ in Figure 8. The voxel size of the CT data was 15.9 μm and therefore, it is likely that small differences in the roughness between the two channels were not captured in the current study, due to a limit in the detectable range of the analysis.

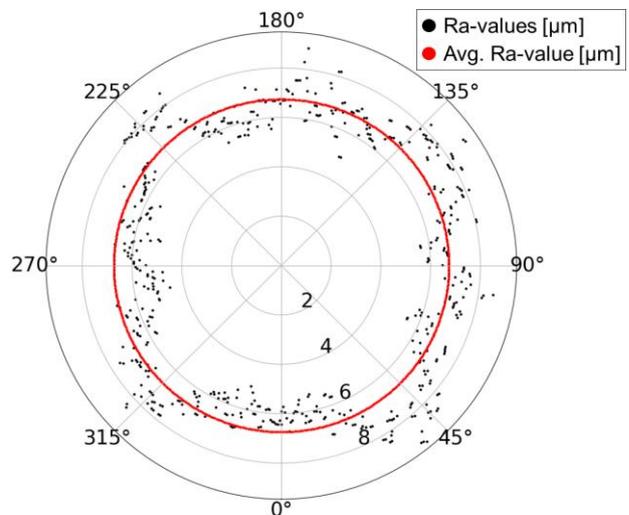


Figure 8. R_a -values as a function of the local orientation β for $\alpha = 90^\circ$.

For $\alpha = 0^\circ, 15^\circ, 30^\circ, 45^\circ$ and 60° , these findings suggest the importance of characterizing the internal surface roughness of

cooling channels with respect to both the global orientation of the channel as a whole and the local orientation within a channel. Due to the voxel size of the CT data used in the current study, it is not possible to fully determine if the local orientation affects the Ra-values differently for $\alpha = 75^\circ$ and $\alpha = 90^\circ$.

3.2. Ra-values dependent on the location along the length of channels

Figure 9 shows a deviation analysis of the channel produced at $\alpha = 0^\circ$ at its full length. The channel was divided into 10 evenly distributed batches and the average Ra-value for each batch was calculated together with the corresponding standard deviation. The figure also shows the channel through-view at three separate locations along the channel. The through-views show how the overhanging roughness is chaotic and changes along the length of the channel.

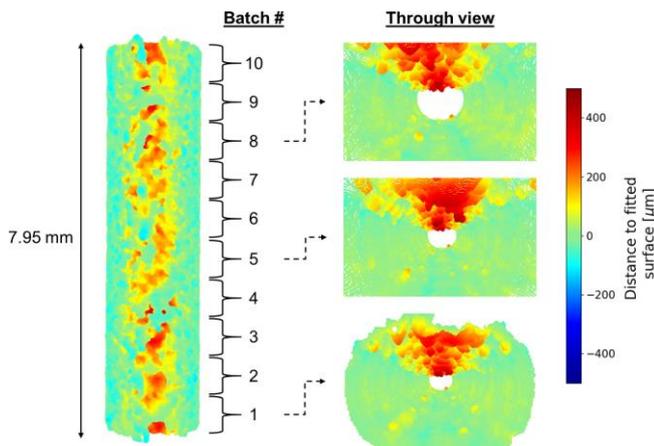


Figure 9. Full length of the analysed channel produced at $\alpha = 0^\circ$ together with the numbered batches and through-views of the channel.

Figure 10 shows the average Ra-values for each of the batches together with their separate standard deviations and the overall average of the batches and the corresponding standard deviation. Once again, the large standard deviations observed for each batch are related to the effect of the local orientation β . As seen from the figure, the average Ra-values are different along the length of the channel. For batch 1, 6, 7, 9 and 10, the

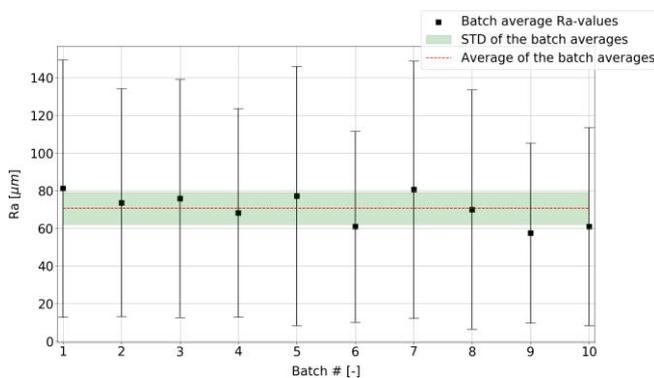


Figure 10. Variation of the average Ra-values along the length of the channel produced at $\alpha = 0^\circ$.

average Ra-values are outside the standard deviation of the overall average, depicted with the green band, indicating a variation in roughness along the length of the channel. The highest difference in Ra-values was seen between batch 7 and 9, where a difference of $Ra_7 - Ra_9 = 81 \mu\text{m} - 57 \mu\text{m} = 24 \mu\text{m}$ was observed. This corresponded to $24 \mu\text{m} / 71 \mu\text{m} \times 100\% = 34\%$ of the overall average, showing a clear difference in the

roughness of the channel, dependent on the location along the length.

4. Conclusions and future work

In this work, seven channels manufactured at different global orientations were characterized by investigating the influence of global and local orientations on calculated Ra-values. The characterization was performed by analyzing the channels using X-ray CT and an in-house Python code for image analysis.

The results showed that the Ra-values were dependent on both the global and the local orientation of the channels. Furthermore, it was shown that the roughness of the channel produced at $\alpha = 0^\circ$ clearly varied along the length of the channel. These findings suggest the importance of full characterization of SLM manufactured cooling channels in terms of both the global and the local orientations and the specific position along the length of a channel.

For future work, it is suggested to look further into the variation of the roughness along the channel length. Furthermore, it could be investigated whether the roughness variation observed through the length is related to α .

Acknowledgments

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