Joint Special Interest Group meeting between euspen and ASPE
Advancing Precision in Additive Manufacturing
Ecole Centrale de Nantes, France, September 2019
www.euspen.eu

Elevated edges of metal parts produced by laser powder bed fusion: characterization and post-process correction

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Abstract
Laser powder bed fusion (LPBF) enables producing very complex geometries compared to conventional subtractive manufacturing techniques. However, the geometrical accuracy of LPBF surfaces remains limited and is often insufficient for applications in high-end sectors such as mould making, medical or aircraft industry. The most common imperfections for horizontal up-facing surfaces include high surface roughness and elevated edges, often called “edge effect”. The surface roughness can be reduced by multiple laser exposure also called “selective laser remelting” (SLR). This work investigates the part’s edge morphology in as-built condition, after SLR, and after SLR combined with a post-process edge removal step by femtosecond laser ablation. This study presents a methodology to characterize the edge of LPBF parts using tactile measurements with a 20 µm spacing between the profiles, thus measuring a 2.5-D surface. The outer edge limit is detected via first and second derivatives of the individual measured profiles, combined with the 2.5-D data. As an outcome of this analysis, the mean and maximal deviation from the desired shape can be assessed in order to determine the material volume to be removed. It was observed that with increasing number of remelting passes the edge slightly flattens out and its center of gravity moves towards the middle of the part. Finally, the efficiency of the corrective post-processing could be assessed, resulting in a maximal deviation of the mean profile of 16 µm.

Edge, Laser beam machining (LBM), Measurement, Selective laser melting (SLM)

1. Introduction

Laser powder bed fusion (LPBF) is an additive manufacturing method allowing an increased design freedom compared to conventional subtractive manufacturing techniques. However, LPBF often does not meet the geometrical accuracy requirements for high-end applications in sectors such as mould making, medical or aircraft industry.

The most common imperfections for horizontal up-facing surfaces include high surface roughness, mostly due to spattering, inadequate connection of adjacent melt tracks [1], and elevated edges of the part [2] (figure 1). The latter phenomenon, commonly called “edge effect”, is mainly affected by the surface tension of the molten material, heat accumulation along edges and the used scanning strategy [3,4].

The edge effect strongly influences the geometrical accuracy of the printed part and can have a detrimental effect on the process stability and deposition of new powder layers [4]. A soft coater blade can be damaged during a collision with the elevated edge and consequently induce surface texture defects, in an extreme case resulting in building job failure [5].

High surface roughness can be reduced by a multiple laser exposure also called “Selective Laser Remelting” (SLR) [6].

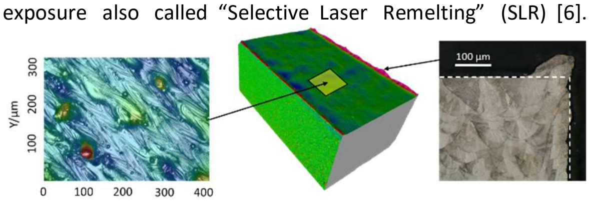

Figure 1. Illustration of most common defects for horizontal up-facing surfaces, high surface roughness (left) and “edge effect” (right).

However, to correct the geometrical inaccuracies in the vicinity of the edge, a subtractive process is necessary, such as mechanical or laser machining. Part edge represents a small local feature, typically about 500 µm long and 100 µm high with respect to the middle surface. Therefore using femtosecond laser ablation to remove this feature seems a viable solution, to avoid alteration of the central surface, possibly already functionalized (e.g. for hydrophobic behaviour).

The edge effect is a challenging feature to characterize, especially after SLR when the surface becomes highly reflective and may be difficult to measure with optical measurement techniques. The advantage of tactile profilometers is that they are not affected by the surface’s optical properties. However, with this technique it is quite challenging to detect the outer limit of the part’s edge.

For the edge detection, it must be considered that the measurement concerns a 2.5-D surface that is convoluted with the probe geometry: a 60° cone ending in a 2 µm diameter ball. As the probe moves down after passing the edge, the probe tip is no longer in contact with the measured surface, and in fact the probe flank is contacted (figure 2). Hence there is not anything

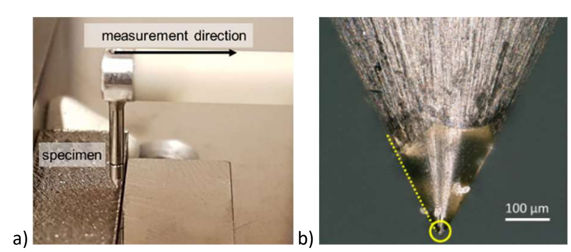

Figure 2. Tactile profilometer. a) Probe moving over part’s outer edge. b) Detail of the probe tip (encircled) and probe flank (dashed line).

Table 1 Overview of the used process parameters.

Laser powder bed fusion	Laser power	150 W
	Scanning speed	1100 mm/s
	Layer thickness	60 µm
	Hatch spacing	70 µm
Selective laser remelting	Hatch spacing	70 µm
Post-process laser ablation	Average laser power	1.5 W
	Scanning speed	600 mm/s
	Repetition rate	500 kHz
	Pulse duration	500 fs
	Hatch spacing	10 µm

like a determined edge to which standard algorithms (Canny, Sobel, etc.) can be applied. Therefore, a different approach is necessary to determine the outer edge limit.

This study presents a methodology to characterize the edge of LPBF parts, applicable to a part before or after SLR, and before or after edge removal by femtosecond laser ablation. The method detects the beginning of the zone where the probe flank is contacted using the first and second derivative of the measured profile. In the next step a linear approximation of the detected edge is considered. With this approach, the variation in shape along the edge and its deviation from the desired shape can be assessed. This way the material volume to be removed can be determined so that a corrective post-processing can be applied, followed by an evaluation of its efficiency.

2. Experimental setup

2.1. Experimental method

For the purpose of this experiment, samples from maraging steel 300 were built on a ProX320 laser powder bed fusion machine from 3D Systems, under argon atmosphere. The samples were designed in 3DXpert software as simple blocks (20 mm x 8 mm x 6 mm) in order to investigate how the selective laser remelting (SLR) strategy influences the edge effect morphology of horizontal surfaces. For this purpose, the top surface was remelted from 1 to 10 times with a 0°, 90° or 120° rotation angle between each remelting pass. The laser power and scanning speed were kept the same as for the building process. SLR was carried out in-process immediately after the last layer was built. Edges of selected samples were corrected by post-process ablation with a femtosecond laser, under ambient air. The scanning direction for ablation was kept along the edge. For more detailed process parameters see table 1.

The 20-mm-long edges were characterized using a Mitutoyo Formtracer CS3200 profilometer and analyzed in Matlab following the procedure detailed in section 2.2. This methodology uses 150 6-mm-long tactile measurements with a 20 µm spacing between the profiles, resulting in a 3 mm x 6 mm 2.5-D surface.

As the tactile profilometer would be damaged while falling from the 6-mm-high sample, a 5 mm gauge block was positioned next to the sample (figure 2a). The surface quality of the gauge block was verified in two perpendicular directions, based on 150 6-mm-long profiles, resulting in an arithmetic mean height on the primary profile Pa=0.099 µm ± 0.006 µm. This means the gauge block surface geometry is sufficiently straight to use it as a reference.

2.2 Evaluation method

The evaluation method as illustrated in figure 3 includes the following steps:

1. Profiles height adjustment

Every individual profile measurement is preceded by lifting the probe and automatic contacting of the surface. This gives a poor repeatability between the height coordinate systems of the profiles. For this reason, each profile height is adjusted using a gauge block on which the probe lands after losing contact with the edge (figure 2a).

2. Slope correction

The profiles are merged into 2.5-D data and the slope is corrected by subtraction of the least squares plane of an area 3 mm x 3 mm, distanced about 0.5 mm from the edge.

3. Detection of the outer edge limit

To detect the location where the probe tip loses contact with the part edge and is moving along its flank (figure 2), we consider the change of slope as a relevant feature. Therefore we use first and second derivatives of the measured profile (see illustration in figure 3a) where the edge limit is determined by a local minimum of the second derivative within a region of negative first derivative. This helps avoiding false positives such as detection of spatters instead of the outer edge limit.

However, as shown in figure 3a, the second derivative is sensitive to noise and the local minimum cannot be detected sufficiently accurately. Hence to detect the local minimum, it is necessary to smoothen the first derivative before proceeding to the second derivative. For this a Gaussian filter according to ISO 16610:21(2011) [7] with λs=80 µm is used.

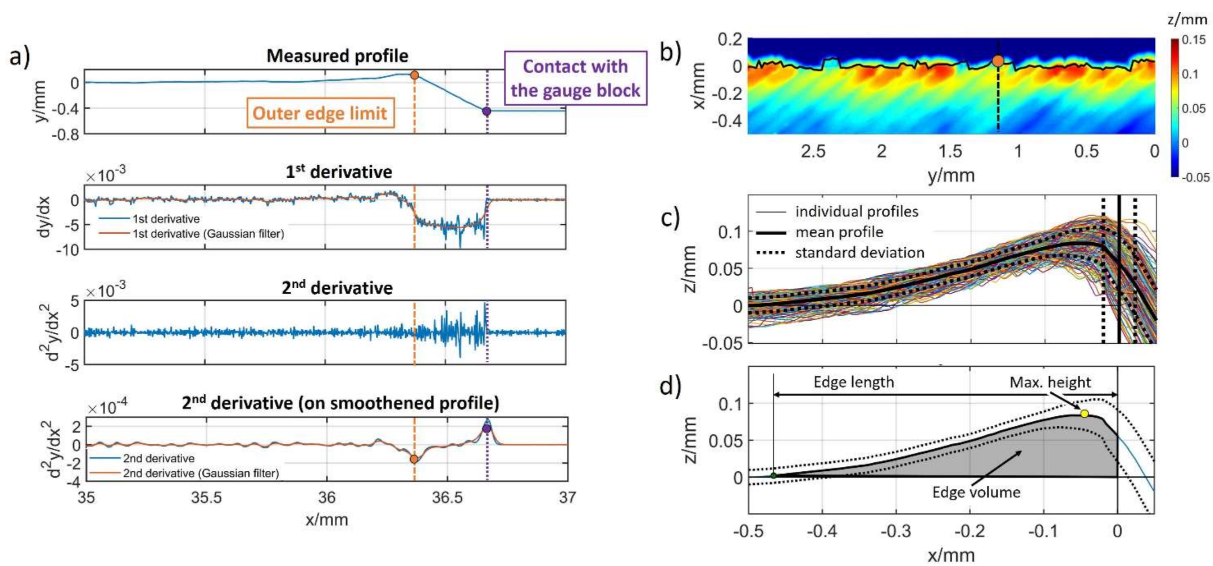

Figure 3. Illustration of the used evaluation method. (a) detection of the outer edge limit on individual profiles, (b) edge detection on individual profiles (dashed line) transferred to the 2.5-D data, (c) mean profile generation and (d) edge parameters determination.

Table 2 Edge morphology at 3 distinct zones of the edge.

	Max. height (mean profile) /µm	Max. height (absolute max) /µm	Edge length /µm	Edge volume /mm³
As-built	75 ± 2	133 ± 3	369 ± 13	0.040 ± 0.002
SLR 1x, 90°	89 ± 5	142 ± 4	439 ± 9	0.063 ± 0.005
SLR 5x, 90°	82 ± 7	111 ± 15	518 ± 21	0.073 ± 0.008
SLR 10x, 90°	76 ± 4	143 ± 30	618 ± 40	0.082 ± 0.001

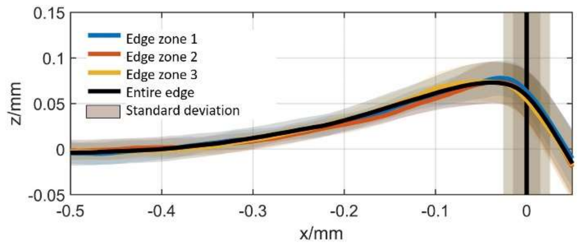

Figure 4. Edge variation of an as-built part.

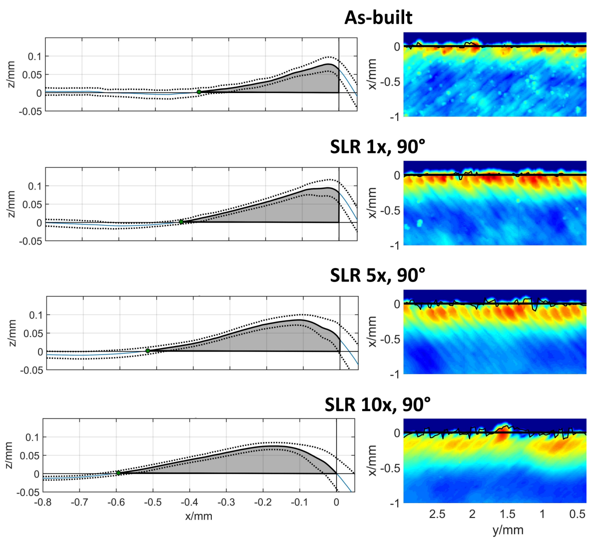

Figure 5. Influence of the number of remelting passes on the edge morphology.

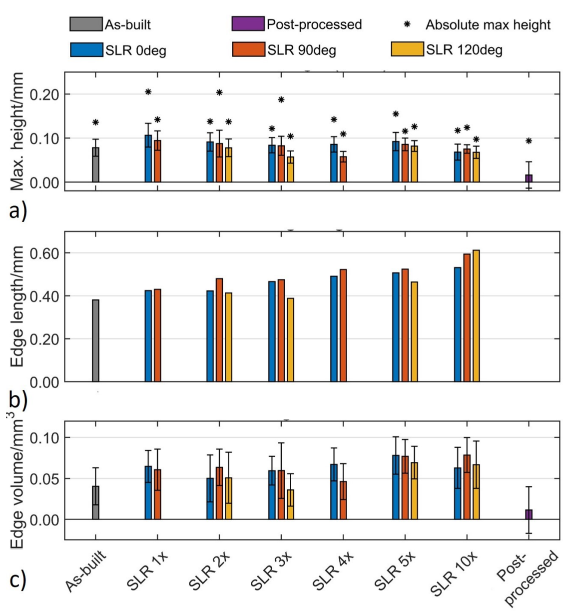

Figure 6. Evolution of (a) the maximal height, (b) edge length and (c) edge volume as a function of number remelting and its angle.

4. Profiles re-alignment

Based on the outer edge limit detected on each profile, the mean edge limit can be determined by a linear approximation (figure 3b). Consequently, the profiles can be re-aligned to compensate for variations in sample's positioning on the measurement stage.

5. Mean edge calculation

In order to characterize the edge morphology to enable post-process or in-situ correction, the mean profile of the edge is calculated, as well as the standard deviation on every point of the mean profile (figure 3c).

6. Edge morphology evaluation

The geometrical deviation of edges of undefined shape is defined by ISO 13715:2017 [8], however the only defined parameter is the maximal distance from the machined side. For a LPBF part's edge, numerous parameters can be used to characterize the edge. In our case we consider the edge delimited by the last zero-crossing and the mean outer edge limit (figure 3d).

In this work the maximal height of the mean profile as well as the absolute maximum height were considered (the latter might correspond to [8]). Furthermore, the edge volume and its length were also determined. The length of an ablated edge was considered equal to the one before ablation.

3. Results and discussion

3.1 Edge variation

The variation of the edge morphology has been evaluated over a distance of 3 mm at 3 different locations, on an as-built sample and samples after 1, 5 and 10 remelting passes (table 2). figure 4 illustrates the variation at these 3 locations compared to the entire edge for an as-built sample.

Table 2 and figure 4 show that the variation is negligible for the maximal height of the mean profile and for the edge volume. A higher variation can be observed for some samples for the absolute maximal parameter which is typically related to isolated particles attached to the edge. This parameter thus includes also the outliers and represents the worst case deviation from the desired shape.

A slightly higher variation was also observed for the edge length parameter, which is very sensitive to the variation of the mean profile slope.

3.2 Edge effect after selective laser remelting (SLR)

Figures 5 and 6 show the evolution of the edge morphology as a function of the number of remelting passes and the rotation angle between them.

As shown in figure 5 and Figure 6a, the maximal height of the mean edge profile seems to increase after the first remelting pass (from 75 µm to about 100 µm). With an increasing number of remelting passes, the maximal height slightly drops to about 70 µm for 10 remelting passes.

Figure 6b shows a slight increase in edge length as well after the first remelting pass (from 380 µm to about 425 µm) which then increases with the number of remelting passes till about 580 µm for 10 passes. The edge volume does not seem to follow any particular trend line (figure 6c). The angle between the remelting passes does not seem to have a significant effect on any of the above mentioned characteristics.

As described by Yasa [2], the edge effect is probably highly related to the first contour vector that is scanned while being surrounded by powder from both sides. This results in a larger melt pool as more powder is drawn into the melt pool due to denudation [9]. The same phenomenon leads to a lower powder supply for the surrounding tracks close to the middle area of the part.

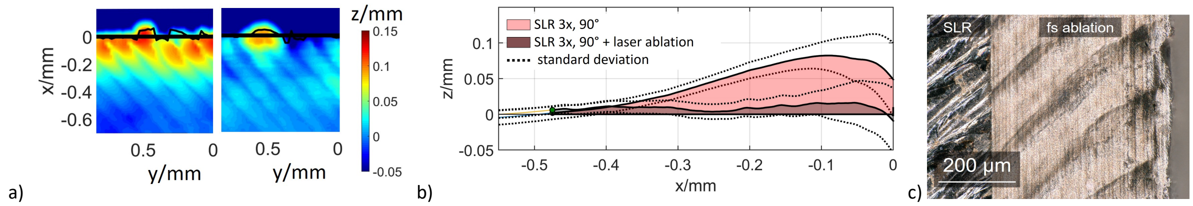

Figure 7. Edge after a post-process correction. a) edge after SLR and after SLR and laser ablation, b) comparison of the mean profiles, c) microscope view on the ablated zone.

In addition the previous, some degree of overheating can still occur despite using the skywriting principle where the acceleration and deceleration of the scanning mirrors happens outside the part at zero power. This probably contributes to a slightly larger melt pool and brings even more powder inside.

It was noted that with an increasing number of remelting passes, the surface tension flattens out not only the middle area of the part, but also tends to flatten out the elevated edges. The edge volume does not seems to be significantly influenced by the number of remelting passes or the rotation angle between them, but considering the decreasing maximal height and increasing edge length, its center of gravity seems to be shifting towards the middle area of the part.

As the main heat input parameters (power and scanning speed) were kept constant, the melt pool dimensions should not be changing significantly, and should be similar to the melt pool dimensions inside the part, with only a limited effect of the number of remelting passes. We can expect the melt pool dimensions including its width to be changing significantly with a higher variation of power, speed and hatch spacing. In such a case, the offset between the scan vectors of the part and those of the remelting passes should be adapted accordingly. Otherwise the melt pool can either not reach the outer edge limit or flood beyond the edge and form thus fine overhanging structures.

3.3 Post-process correction of the edge effect

As shown in figures 6 and 7, the maximal height and volume could be significantly reduced using femtosecond laser ablation. The maximal height dropped from 82 µm to 16 µm, and the edge volume from 0.060 mm^3 to 0.011 mm^3. However the edge variation after ablation was observed to be relatively high, in fact very close to the one after SLR. Using ultra short pulses enables obtaining very neatly ablated surfaces (figure 7c), but no or very little melting occurs during the process. In simplified terms, the ablated edge can be directly approximated as a subtraction of the mean edge value from the original edge, thus the edge variability remains about constant.

Also a correct positioning of the scanning vectors for ablation is crucial. As shown in figure 7a, a particle attached to the edge was not completely removed. As a result, the maximal height based on the mean profile was considerably reduced (figure 6a). Nevertheless, the absolute maximal height was not reduced due to these isolated particles which remain attached to the edge.

4. Conclusions

The edge effect of LPBF parts in maraging steel was evaluated using the above described method. With an increasing number of remelting passes, a decreasing maximal height and increasing edge length were observed. The edge volume seems to remain approximately constant, and the center of gravity of the edge seems to shift towards the inner areas of the part.

The mean profile generated from this analysis allowed a laser-based post-process correction increasing the geometrical accuracy of the finished part. The maximal edge deviation was reduced by a factor of 5, from 82 µm to 16 µm above the middle surface mean plane. However the edge variability remained relatively high even after post-processing.

To achieve an even better correction of the geometrical inaccuracies, an additional melting pass might be a possible solution. The KU Leuven Additive Manufacturing team is currently investigating the possibility to correct the edges in-situ during the LPBF process using a nanosecond pulsed wave laser and possibly combined with an additional remelting pass after the erosion pass.

Acknowledgements

This research was funded by EU ITN project PAM² (Precision Additive Metal Manufacturing) H2020 - Grant Agreement No 721383, and Hylaform - the infrastructure platform HyLaForm, funded by the Flemish government (2016).

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