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Evaluation of offline path planning for laser metal deposition on freeform surfaces

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Abstract

The thickness of a layer made by Laser Metal Deposition (LMD) on a freeform surface varies depending on the local angle of inclination and the tool path direction. When depositing multiple layers, the CAM (Computer-Aided Manufacturing) planning for the tool paths requires an accurate description of the surface topography of the previous layers to ensure a stable process. Offline path planning is commonly based on the translation of the surface in the building direction (z-offset) or in the direction of the plane normal after each layer. In this paper, troughs with freeform surfaces are filled via LMD. The surface topography is measured after each layer and its deviation against the calculated surface according to z-offset and plane normal method is evaluated. Advice is given on which method of offline path planning is preferable and if additional controlling measurements of the surface are necessary after a certain amount of layers.

Keywords: Laser Metal Deposition; CAD; CAM; Reverse Engineering; Offline path planning

1. Introduction

Laser Metal Deposition (LMD) is an Additive Manufacturing (AM) technology that uses a laser beam to create a melt pool on a substrate surface into which a filler material is injected and melted. The filler material is a metallic material and can be supplied as a powder or a wire. After solidification of the filler material, a track of deposited material is formed. In order to deposit a layer of the filler material, multiple tracks are deposited with a defined overlap of 30-50%. Three-dimensional structures are built by adding layer upon layer.

Metal powder filler material is supplied by nozzles whose focal point has to be set on the substrate surface. In case the distance between nozzle and substrate surface becomes too small, parts of the powder are not melted in the melt pool and are wasted for the process. The height of the deposition is reduced and in the subsequent layer, the distance between nozzle and substrate surface is increased so the process remains stable. However, powder efficiency is reduced and process time increases. In case the distance between nozzle and substrate surface becomes too big, parts of the powder are not injected into the melt pool and the height of the deposition is reduced. In the subsequent layer, the distance between nozzle and substrate surface increases further which leads to a reduced height of the deposition again until the process becomes unstable and no more material is deposited (Garmendia et al., 2018).

LMD is often used as a technology for the repair of turbine blades or other components with freeform surfaces (Pinkerton et al., 2008). These freeform surfaces present inclinations with locally different angles. The height of deposited

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single tracks and layers depends on the local inclination of the surface and on the scanning direction of the nozzle. E.g., scanning from the bottom to the tops results in bigger deposition heights than scanning from the top to the bottom. As a result, the anticipated height differs from the height that is in fact deposited on the substrate (Lin and Hwang, 1999). However, the path planning for an LMD process is usually done offline which means that deviations of anticipated and deposited height of the material are not examined during the process and the path planning cannot be adjusted to those deviations. Over the course of multiple layers, these deviations can add up and lead to an instable process when the distance between the nozzle and the surface becomes too big (Garmendia et al., 2018). To stabilize the process, the focal point of the nozzle can be set slightly below the substrate surface. In this case, the powder efficiency increases if the distance between nozzle and surface substrate increases slightly and the deviation can be reversed. However, the correct estimation of layer heights is still crucial for a path planning technique that ensures a stable LMD process.

Offline path planning should be based on layer geometries that have the smallest deviations to the surface of the substrate after n deposited layers of material so that both a stable and efficient process can be achieved.

Two different approaches of estimating the surface geometry for offline path planning will be examined in the present work; the first approach uses the translation of the surface geometry in the z-direction (building direction) of the estimated layer height for path planning of the following layer. This method will be referred to as “z-offset method” in this work. The second approach (“n-offset method”) uses the translation of the surface geometry in the local normal direction of the surface of the estimated layer height for path planning of the following layer, see Fig. 1. The estimated layer height is equivalent to the height of a single layer deposition on a non-inclined plane which is evaluated prior to the path planning (Graf et al., 2012).

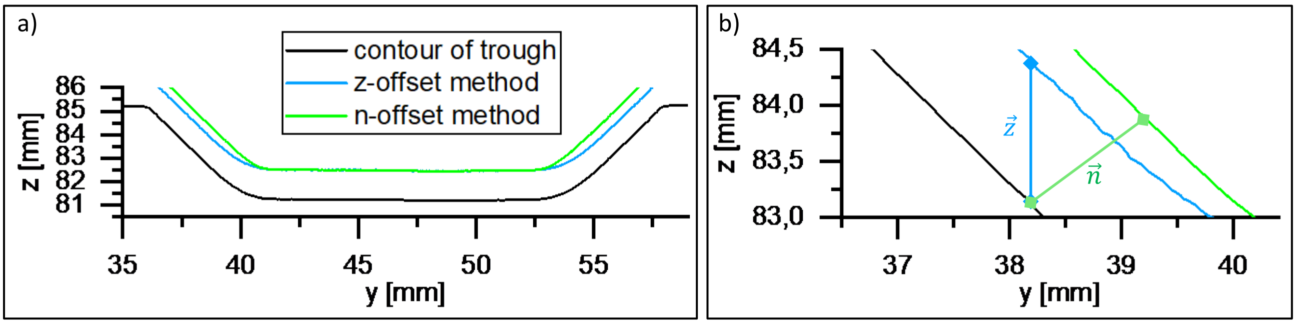

Fig. 1. a) Cross section showing the contours of the trough and planes calculated by translation along the z-direction and plane normal direction; b) Close-up of the contours at the edge of the trough illustrating the difference of z- and n-offset methods

When using LMD to fill troughs in components, there are various approaches concerning the scanning strategy. A trough can be filled layer-wise from the bottom to the top and each layer is set to a fixed z-coordinate, filling the trough similarly to filling a bathtub, see Fig. 2 a) to c). Using this method, deposition on inclined planes can be avoided and the offline path planning will lead to a stable process. However, in each layer, start and end points of the deposition tracks lie in the center of the component part. Start and end points are weak spots due to the adhesion of powder and increased likelihood of pore formation and can cause crack formation and the failure of the component (Graf et al., 2012).

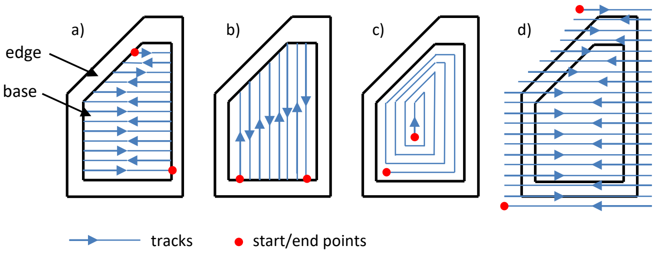

Fig. 2. a), b), c) Methods to fill a trough similarly to a bathtub: start and end points lie within the trough, d) method of filling a trough with start and end points outside of the trough requires deposition on inclined edges of the trough

In order to eliminate starting and end points of the deposition from the inside of critical parts of the component, the deposition tracks start and end outside of the trough and are milled off in post-processing. This requires deposition on inclined planes on the edges of the trough, see Fig. 2 d).

In this work, offline path planning based on z-offset and n-offset method. Path planned by both of these methods are deposited into the trough and topography scans are carried out after the deposition of each layer. Deviations between theoretical surface geometry that is used for offline path planning and the actual surface geometry are evaluated and used for the development of an improved method for estimating the surface geometry for offline path planning. A “quasi-online” path planning method is carried out by using the topography scans after each deposited layer for the path planning of the subsequent layer. This method is used as reference for the improved path planning method.

2. Experimental

Experiments were carried out on a laboratory LMD system equipped with a 3 kW Nd:YAG laser by Trumpf GmbH & Co. KG, Ditzingen, Germany, and 5-axis-CNC-system. A 40 mm coaxial powder nozzle by Fraunhofer Institute for Lasertechnology (ILT), Aachen, Germany, and Single 10-C powder feeder by OC Oerlikon Corporation AG, Freienbach, Switzerland, were used for the supply of IN718 powder of 45 – 90 µm particle size by TLS Technik GmbH, Bitterfeld, Germany. Process parameters are listed in Table 1. Single tracks had a width of 1000 µm and a height of 250 µm, single layers deposited with an overlap of 50% had a height of 330 µm. Path planning was done with the software “LMDCAM2” developed at Fraunhofer ILT. Paths followed a meander track across the trough and were rotated by 90° after each layer.

Table 1. Process parameters

Process parameter	
Laser power P_L	310 W
Laser beam diameter d_L	1 mm
Scanning speed v_s	500 mm/min
Track overlap	50%
Powder mass flow $\dot{m}_p$	0.75 g/min
Shielding gas flow $\dot{V}_{SG}$	5 l/min
Conveying gas flow $\dot{V}_{CG}$	2 l/min

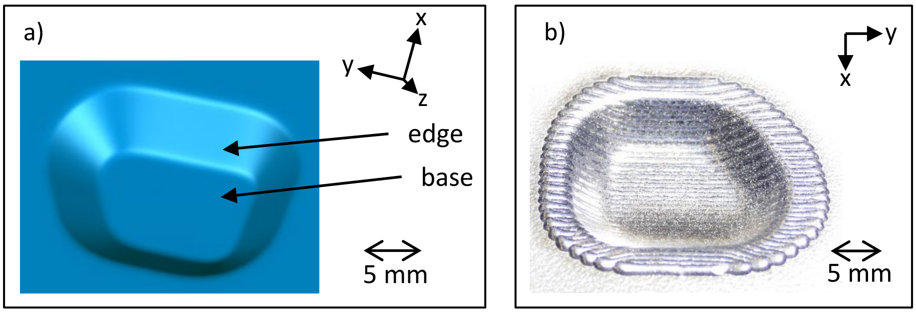

Fig. 3. a) Trough used to evaluate z- and n-offset methods for offline path planning, b) Deposition of one layer in the trough

3. Results and Discussion

3.1. Deviations between surface geometry of deposited material and expected surface geometry based on z- and n-offset methods

Deviations of the expected surface geometries after 4 and 8 layers with regard to the surface geometry of the deposited material are evaluated in false color images for both planning methods, z- and n-offset method. For each layer, only the area where material is deposited is evaluated, which means that the evaluated area of layer 8 is smaller than that of layer 4. Also, cross sections trough the trough showing the contour of expected and deposited surface geometry are evaluated in layer 8. The position of the cross sections is shown in Fig. 4.

Fig. 5 shows the deviation of expected surface geometry by the z-offset method and the surface geometry of the deposited material after 4 and 8 layers. Negative values signify that more material is deposited than expected by the offline path planning method. In the base of the trough, the surface geometry of the deposition shows deviations of 0 to 150 µm (layer 4) and 0 to 200 µm (layer 8) to the expected surface geometry. At the edges, up to 600 µm more material is deposited than expected by the offline path planning method after four layers. After eight layers, the deviation between expected and actual surface geometry at the edges is up to 900 µm. The deviation does not increase linearly with the number of layers, since the self-regulatory effect of too large deposition heights reduces the powder efficiency.

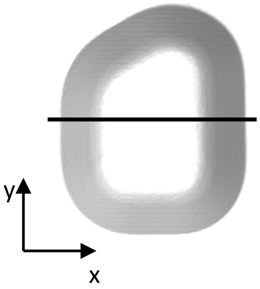

Fig. 4. Position of the cross section for evaluation of the deposition after layer

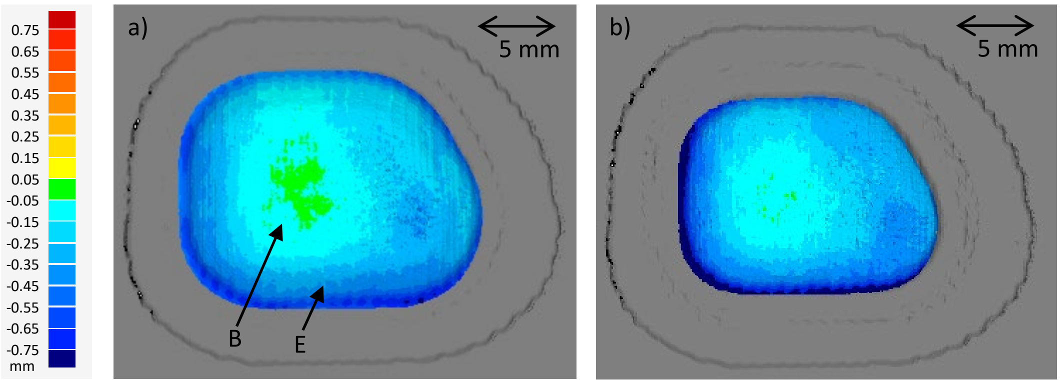

Fig. 5. Deviation of deposition height expected by z-offset method and actual deposition after a) four layers and b) eight layers. Negative values correspond to a higher deposition than expected by the z-offset method. Deviations are below 200 µm at the base of the trough (B); at the edge of the trough (E), deviations reach 600 µm and 900 µm deviations after 4 and 8 layers, respectively.

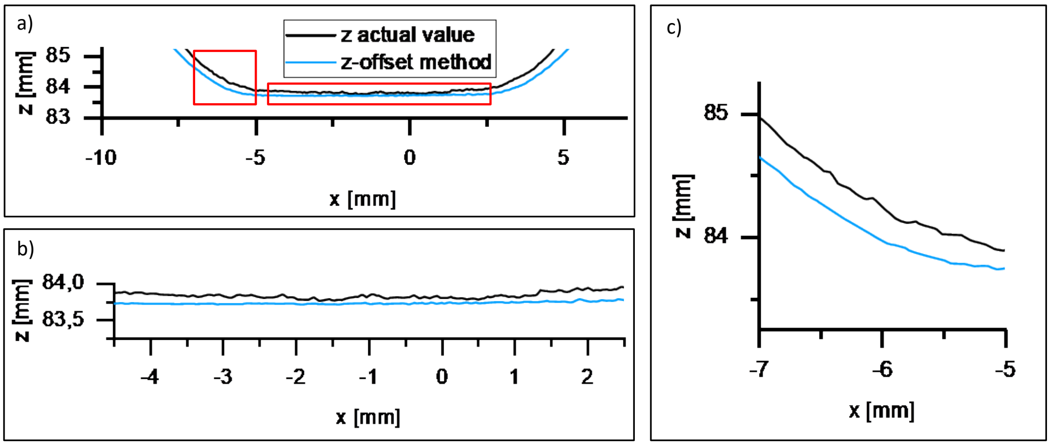

Fig. 6. a) Cross section of the contour with measured height (black line) and the expected height based on planning with the z-offset method (blue line). The deposited height matches the expected height at the base of the trough (b) and is bigger than the expected height at the edges of the trough (c).

The cross sections of the surface contours after 8 layers carried out with offline path planning based on the z-offset method are shown in Fig. 6. Deviations up to 200 µm can be seen in the base of the trough. At the edges, the deviation increases towards the rims of the trough, growing from 200 to 900 µm. The accumulation at the rim is caused by the turning points of the meander paths.

Fig 7. shows the deviation of expected surface geometry by the n-offset method and the surface geometry of the deposited material after four and eight layers. Positive values signify that less material than expected was deposited. In the base of the trough, expected and actual surface geometries show deviations of 0 to 150 µm (layer 4) and 0 to 200 µm (layer 8). At the edges of the trough, deviations rise up to 350 µm (after 4 layers) and 450 µm (after 8 layers). The deviations do not increase linearly since the powder focal point is set to be below the surface to ensure an increased stability of the process in case of reduced deposition.

The cross sections of the surface contours after 8 layers carried out with offline path planning based on the n-offset method are shown in Fig. 8. At the base of the trough, the deviation is up to 200 µm whereas the deviation at the edges rises from 200 to 500 µm. In layer four, a slightly excessive accumulation of material is observed at one rim which can be explained by increased deposition of material at the turning points of the meander scanning technique.

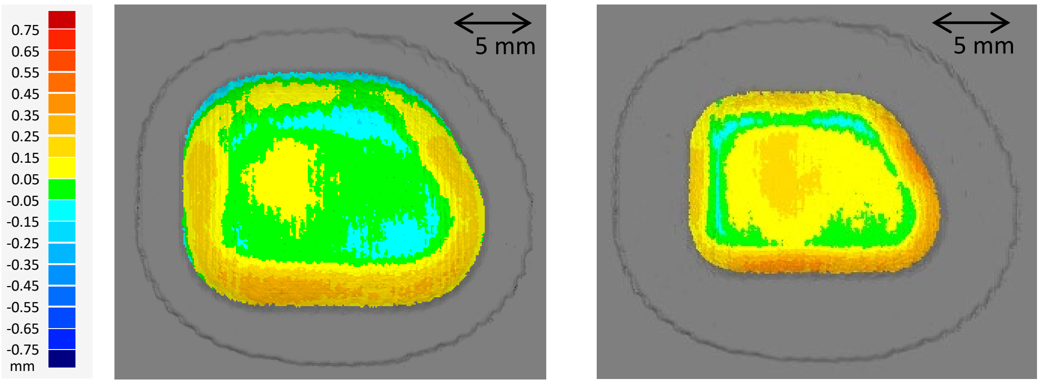

Fig. 7. Deviation of deposition height expected by n-offset method and actual deposition after a) four layers and b) eight layers. Positive values correspond to a lower deposition than expected by the n-offset method. Deviations are below 200 µm at the base of the trough; at the edge of the trough, deviations reach 350 µm and 450 µm deviations after 4 and 8 layers, respectively.

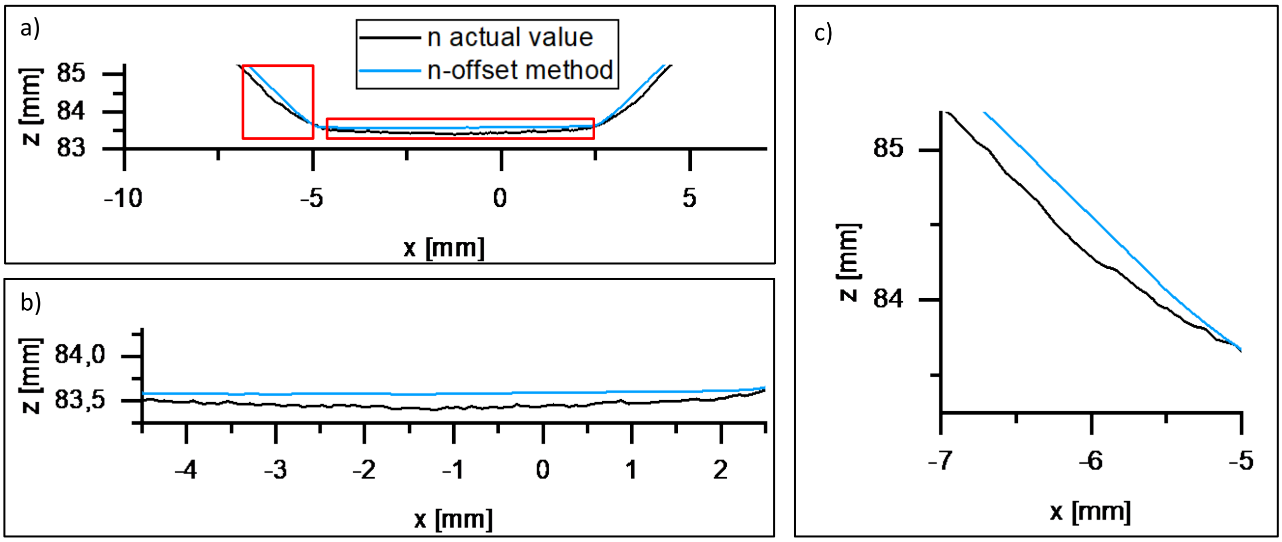

Fig. 8. (a) Cross section of the contour with measured height (black line) and the expected height based on planning with the n-offset method (blue line). The deposited height matches the expected height at the base of the trough (b) and is smaller than the expected height at the edges of the trough (c).

3.2. Suggestion of an improved method for offline path planning

As seen in section 3.1, both offline path planning methods have deviations of the same magnitude but with opposite signs. By taking the average of both planning methods, the offline planning method can be improved. This method will be referred to as "average method" within this work. A cross section showing the contours of the trough and surfaces calculated by z-, n-offset and the average method is shown in Fig. 9. The planning methods are identical at the base of the trough, but at the edges, the average method can be seen as the compromise between z- and n-offset methods which expect small or big depositions, respectively.

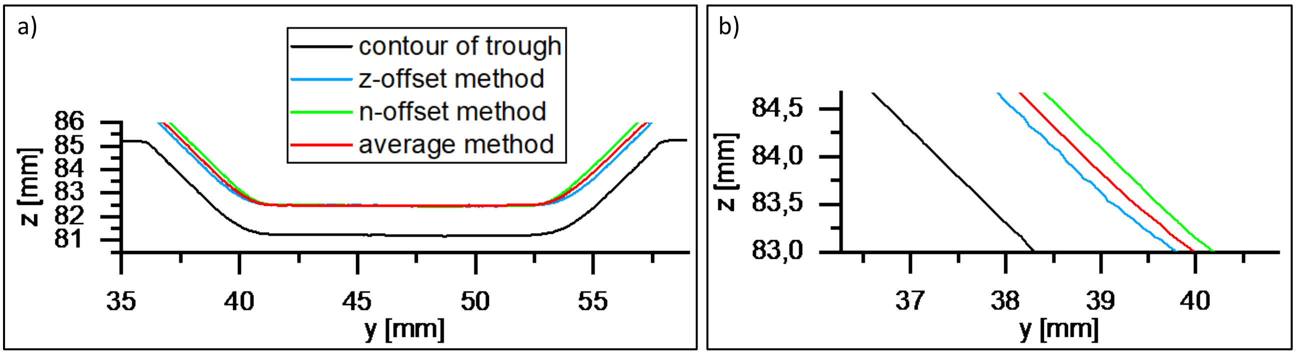

Fig. 9. a) Cross section showing the contours of the trough and planes calculated by z- and n-offset method and the average method; b) Close-up of the contours at the edge of the trough illustrating the relative positions between the contours of planes based on of z- and n-offset methods and the average method

The expected surfaces based on the average method are compared to surface geometries of the "quasi-online" path planning. For the "quasi-online" path planning, scans of the surface of each layer are used to calculate the paths for the subsequent layer and should present the optimal paths. Fig. 10 shows the deviation of expected surface geometry by the average method and the surface geometry of the deposited material by "quasi-online" path planning after four and eight layers. After four layers, deviations at both base and edges of the trough are below 250 µm. The average deviations are 60 µm where too little material is deposited and 110 µm where too much material is deposited. After eight layers, deviations range between 0 and 250 µm except for accumulations at the rim caused by the turning point of the meander tracks. The average deviations are 60 µm where too little material is deposited and 120 µm where too much material is deposited. The deviations remain constant over the course of 8 layers and do not pose a threat for instability of the process.

The cross sections of the surface contours after 8 layers carried out with "quasi-online" path planning and the expected surface geometry based on the average method are shown in Fig. 11. At the base and the edges of the trough, the deviation remains below 150 µm except for accumulation at one side of the rim caused by the excessive deposition at the turning points of the meander tracks.

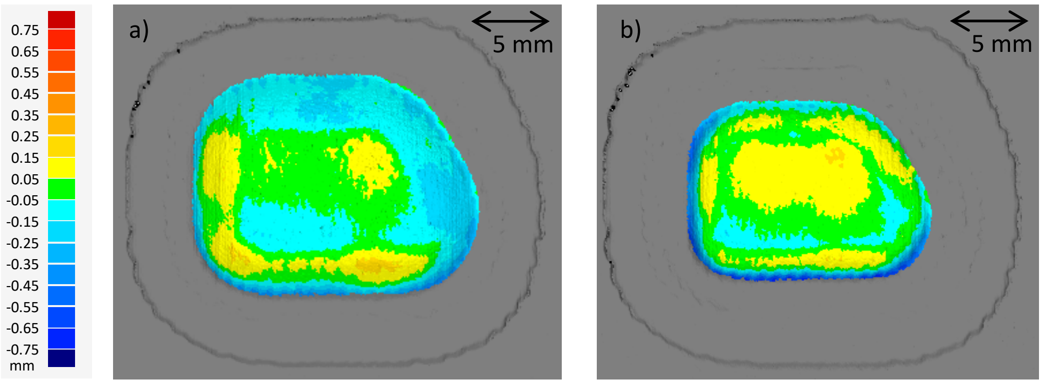

Fig. 10. a) Deviation of the depositions based on "quasi-offline" path planning and the expected depositions based on the average method after a) four layers and b) eight layers. Deviations are below 250 µm after four and eight layers. Average deviations for too much deposited material are 110 and 120 µm after four and eight deposited layers, respectively. Average deviations for too little deposited material are 60 µm after four and eight deposited layers.

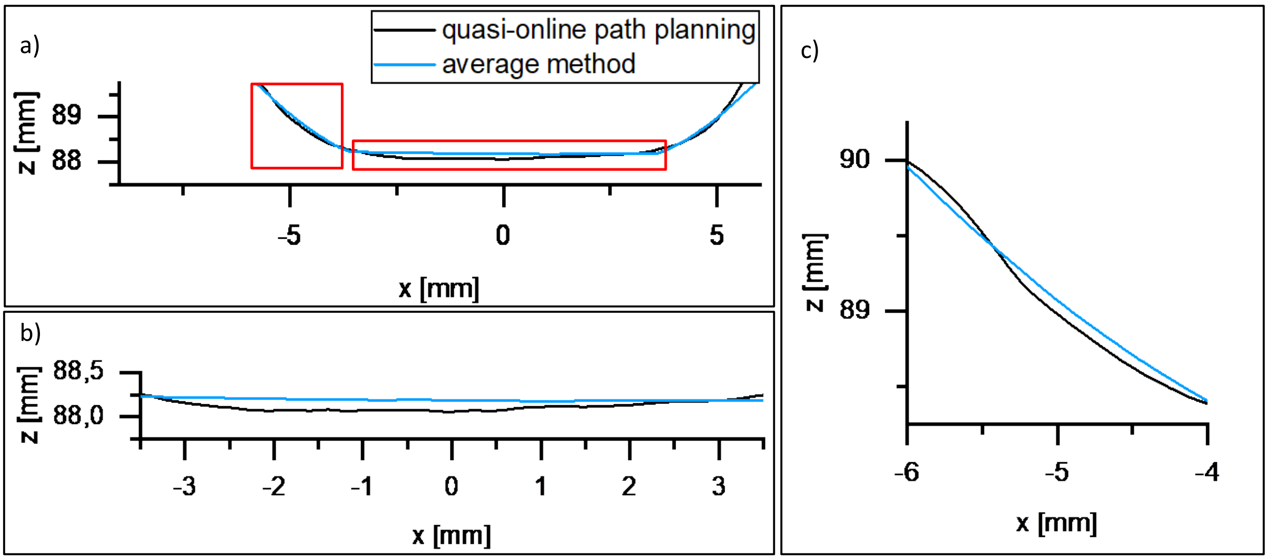

Fig. 11. a) Cross section of contours by deposited material based on “quasi-online” path planning (black line) and expected deposition surface based on the average method (blue line). Geometric deviations both at the base (b) and the edges (c) of the trough remain below 150 µm except for at one rim (x>5 mm) of the trough due to excessive accumulation of deposited material caused by the turning points of the meander tracks.

4. Conclusions

Offline path planning based on the translation of the surface geometry in the z- or building direction leads to deviations at inclined planes. More material is deposited than expected by the method. This can be balanced by the self-regulatory effect of a reduced distance between nozzle and substrate surface. However, the reduced distance leads to a waste of powder and increased process times.

Offline path planning based on the translation of the surface geometry in the direction of the local plane normal leads to deviations of the expected surface geometry at inclined planes. Less material is deposited at the inclined planes than expected. The distance between nozzle and substrate increases which leads to even less deposition and can cause the process to become instable.

An intermediate offline path planning method is proposed which uses the average surface of the surfaces obtained by the translation in z- and plane normal direction. Deviation at non-inclined planes remain low while deviations at inclined planes are reduced to <150 µm.

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