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Laser Ablation Adaptive Slicing for Shape Deviation Control of Additively Manufactured Parts

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Abstract

Laser ablation considered as a subtractive process working alongside an additive system promotes the geometric integrity of components and compliance with the nominal design. The strategy chosen to remove build deviations has a fundamental role towards streamlining efficient digital workflows for layer-wise manufacturing of high-quality components. A variable slicing algorithm is proposed for the adaptive ablation of in-process reconstructed over-sized volumes considering the laser-material interaction, a layer manufacturing priority list and volume characteristics. A first verification shows that the flexible change of the ablation slicing strategy hold potential for implementation within a hybrid process chain for additive manufacturing.

Keywords: laser ablation; adaptive slicing; hybrid manufacturing

1. Introduction

Additive manufacturing (AM) operates by adding layers of material together to build an object. Nowadays the AM landscape includes a range of various layer-by-layer technologies, each with its own specific benefits, drawbacks and application areas. They all share though one central concern related to the dimensional and form accuracy as well as the surface finish of manufactured parts. These are still seen as a bottleneck for the AM quality control [1].

Amongst the existing powder-based technologies the laser metal deposition (LMD) is particularly interesting for both the deposition of green field parts and the realization of localized coatings and restoration applications. Nevertheless, the produced parts typically deviate from the targeted net shape and a certain amount of post processing is required to guarantee the consistency with CAD data. Undesired irregularities add up over multiple layers and lead to error propagation which influences not only parts' shape and surface quality but also their mechanical properties [2]. Therefore, manufacturing methods capable of reliably removing deposition defects while delivering similar digital flexibility as the layer-wise additive production are in demand [3]. Layer ablation is a non-contact process which takes advantage of the qualities of a laser tool combined with a high degree of flexibility and easy integration opportunities to automate the selective post processing of AM parts. Its layer-by-layer material removal potential was proved for many years for engraving, laser marking and micro machining applications across various difficult-to-machine materials [4].

More recently hybrid-AM by ablation gained interest promoted by the ablation's capability to improve the accuracy in build direction by reducing the layer thickness or removing irregularities as well as to reduce the surface roughness [5]. However, the high irregularity of the AM shape deviations raises issues regarding the control of the removed depth of material for any post-processing activity involving laser ablation. Whereas with conventional post-processing operations such as milling the results of the machining operation are completely determined by the geometry and position of the tool this is not the case with laser ablation. When the laser parameters are not optimized it is very likely to run into inconsistencies when the actual depth of cut and material removal rate values are compared with the nominal ones [6].

This paper introduces an adaptive slicing engine to efficiently synchronize the laser beam focus distance with the depth of material removed per layer during the selective ablation of irregular AM part shape deviations. The proposed engine is a subpart of an automated hybrid AM workflow which promotes the geometric integrity of AM parts through recursive additive and subtractive operation sequencing and planning activities with the support of an in-process inspection operation.

2. State of the art

A literature review related to laser precision machining has shown that most of the studies focused on investigations of the heat affected zone and thickness of the recast layer as well as on the improvement of the surface topography and the material removal mechanisms [7].

The importance of optimized slicing, tool path and material removal strategies on the resultant surface quality, edge definition and thermal load management during the laser machining of micro cavities was raised by [8]. The slicing optimization was merely discussed in the light of ensuring compliance of the slices with the original part contour.

Laser polishing and cleaning were reported as effective post-processing treatments for the surface topography improvement of steel and aluminum parts manufactured by selective laser melting [3]. Satisfactory results in terms of surface quality were obtained also by alternating the laser metal deposition and laser polishing with respect to non-accessible surfaces in the building machine [9].

The process and parameter selection are essential not only to achieve acceptable roughness but also to optimize the material removal rate. Unlike conventional milling technologies the control of material depth removed every pass by laser ablation introduces uncertainties due to the correlation between many factors. A modelling framework and experimental investigations for the prediction of features produced by nanosecond lasers on Ni- and Ti-alloys by considering material removal and material redeposition functions were proposed by Cha et al [10]. Another work focusing on the surface roughness and removal rate of a laser ablation technique applied for the finishing of additively manufactured die cutting edges was put forward by Hallmann et al. [11]. Profile shape generation with high dimensional accuracy and good surface finishing was achieved in a single step considering the finer resolution and absence of cutting forces obtained when processing a material with a high intensity laser beam with respect to conventional chipping tools. The layer thickness, scanning speed, pulse frequency and laser power have been found to have a significant contribution to the final surface quality and maximum ablation rate obtained during the laser beam machining of Inconel 718 [6,12]. To further expand the capabilities of laser-based technologies to process the Inconel 718 few research works discussed the benefits of integrated hybrid workflows. Arrizubieta et al. [13] promoted the concept of combining LMD and laser beam processing (LBM) processes aiming to remove the surface waviness that LMD generates, and hence, to obtain a flat surface. Scanning velocity, pulse frequency and pulse duration were varied to determine the best process recipe while the position of the laser beam focus remained unchanged as the number of ablation repetitions was increased. Another hybrid manufacturing study highlighted the potential of the laser ablation to enhance the geometric accuracy and surface quality of LMD parts with focus on restoration applications [14]. Firstly, the ablation of rectangular cavities on an Inconel 718 substrate was performed to simulate the preparation of a damaged surface for a subsequent LMD operation. After the LMD restoration two ablation process recipes were subsequently run on the as-deposited feature by changing the values of the laser power, pulse frequency and number of ablation passes. The final analysis demonstrated a good planarity and improved surface roughness but also the presence of an over-deposit material.

The described applications showed on one hand the potential of LBM to provide beneficial results in terms of surface quality and ablation rates for the post processing of regular features. On the other hand, it emphasized the need for new ablation strategies to ensure the respect of targeted net shape of AM parts when the starting shape of the unavoidable geometric deviations requiring removal is irregular.

3. Material and equipment

The material selected for the experimental verification is Inconel 718, a nickel alloy well known for maintaining its mechanical properties at high temperature and generating elevated cutting forces and strong abrasive tool wear during conventional machining [15]. Particularly, its poor machinability recommends it as a good candidate for laser processing techniques. For the LMD tests a spherical gas atomized powder (MetcoAdd 718F, supplier Oerlikon AM ®) with a grain size ranging between 45 and 106 μm was employed.

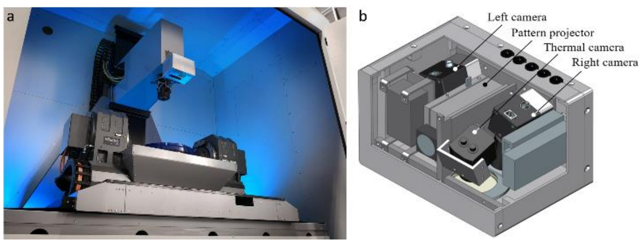

Fig. 1. (a) 4D Hybrid machine; (b) Vision Box hardware components

All experiments were carried out on a hybrid machine realized for the H2020 4D Hybrid project which gathers together within the same envelope laser metal deposition, laser ablation and 3D scanning. The 4D Hybrid system (Fig. 1a) is a 5-axis machine (3 Cartesian axes and a 2-axis rotary table) endowed with an optical chain which accommodates two laser sources: 1 kW continuous wave laser source used for deposition and a 100 W nanosecond pulsed wave laser source for ablation. The pulsed fiber laser has a central emission wavelength of 1064nm and its maximum pulse repetition rate is 500 kHz. For a pulse repetition rate of 100 kHz the average pulse duration is 100ns and pulse energy is 1mJ. The laser fibers are plugged into a laser beam combiner, a device capable of selecting the desired beam by a moving mirror. The laser optical chain is completed by a 2-axis RAYLASE laser scanner, equipped with an F-Theta lens, which allows to operate laser ablation with a spot of 0.1 mm at high speed (18 m/s) on localized patches of the target surface, at a specific focal plane. The hybrid machine is equipped also with a sensing system embedded into the gantry-structure and called Vision Box (VB). The VB (Fig. 1b) contains hardware components to monitor and control the melt pool shape, temperature distribution, and actual part geometry. The VB is connected to an external PC that manages scan triggering and processing, as well as the communication with the machine PLC for synchronizing the machine poses with the part geometry acquisition.

4. Methodology

The proposed adaptive slicing engine relies upon an empirical modelling technique to estimate the amount of material removed in function of the ablated area. In order to characterize the laser-material interaction an extensive number of experimental runs were initially performed. The ablated object was a square with the side size of 6mm and the parameters considered for variation were the laser power, pulse frequency, scanning speed, filling space, hatching method and number of passes. The performance of each ablation recipe was evaluated in terms of the melt burr formation, taper angle of the walls, peak-to-valley height and surface roughness on the bottom of the engraved area. The external inspection of the realized samples was performed with a Keyence® VHX6000 digital microscope using a 200x zoom with a sensibility of 1.08 microns in X and Y directions and a Z sensibility of 1.5 microns. The best performing recipe was selected and employed for the subsequent tests. The aim of these tests was to monitor the total depth reached after 25 ablation passes performed on square objects of different areas (Fig. 2a). The process parameters are detailed in Table 1.

Table 1. Ablation parameters

Laser power [W]	67.5
Frequency[kHz]	50
Scanner speed [mm/s]	1000
Filling space[mm]	0.01
Number of Passes	25
Strategy	Parallel Bidirectional
Laser spot [mm]	0.1

The measured amount of material removed for each ablation pass is shown in Fig. 2b. Higher ablation depths can be achieved under low scanning speeds and this seems to be significantly influenced by the area to be scanned as the setpoint scanning velocity cannot be reached for short laser paths. A clear trend could be identified in function of the dimension of the square: for small areas (i.e. below 3 mm of square's side) there is a pseudo-exponential behavior; the smaller the area, the higher the quantity of removed material with a maximum in the range of 7µm/pass measured for the square with a side length of 0.5mm. For larger geometries (i.e. over 3 mm of square's side length), the trend tends to converge towards a constant value near to 4 microns per pass. An exponential regression was used to fit a model to these data (Fig. 2b). The exponential curve fitting laid the background for the implementation of a slicing algorithm to adapt the layer thickness in function of the geometry of the over-sized deviations detected in AM parts.

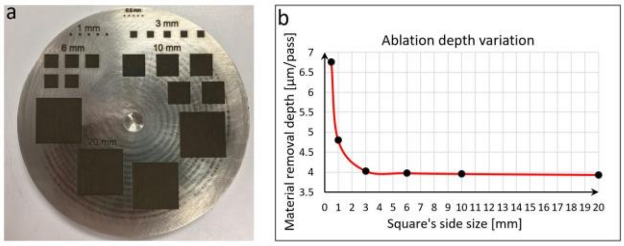

Fig. 2. (a) Substrate with ablated squares of various sizes and their repetitions; (b) regression curve of the material removal

Its architecture is shown in Fig. 3. The main input is provided by an inspection operation realized with the 3D scanner located inside the machine's VB. The result of this activity is a cloud of points describing the current geometrical and dimensional status of the AM part.

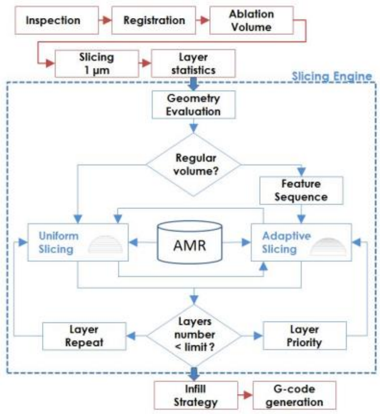

Fig. 3. Adaptive slicing algorithm

After the inspection, a registration with the nominal CAD is performed and both positive and negative deviation volumes are extracted. The volume to be ablated is prepared subsequently based on specific technological constraints related to both additive and subtractive operations of the hybrid manufacturing workflow.

The following step consists of a preliminary slicing of the ablation volume with a layer thickness of 1µm. This activity supports the characterization of the deviation volume based on a series of statistics pertaining to the generated layers: number of contours within each layer, area of each contour, minimum distance between the contours, Z-level for each layer, and total surface area overlaps between consecutive layers. In the geometry evaluation step a decision is made regarding how to handle the volume to be ablated, either as a regular or as an irregular shape. All volumes falling under the category of extruded shapes with vertical walls will be considered regular and will be processed as single features by employing the uniform slicing approach.

The uniform slicing considers exclusively the total area of the layers and a user defined tolerance factor for the layer surface area overlap to define a constant ablation layer thickness. The resulted number of layers must be checked against the maximum allowable number of layers, which is currently a limitation of the laser scanner's board control memory. In case more than 200 layers are generated the slicing will be reiterated by considering the multiple repetition of every n layer until the limit condition is met, where n= (2, 3, ...).

The analysis of the 1µm slice area overlap measurements, contour counts and distances between contours identified within the same layer is used to decide how to process irregular volumes. A particular consideration is given to the identification of individual features and section changes within the topology of the deviation volume. This activity triggers the definition of a processing sequence for the identified features and the split of each feature in sections based on the topology of each feature. In this case the uniform and adaptive slicing could be alternatively employed for the strategy preparation. For instance, if one of the features of the volume has a regular section the uniform slicing algorithm will be invoked. Upon the completion of the slicing strategies for all features and sections the final strategy for the entire irregular volume will be released. Regardless of the slicing method employed, the value of the layer thickness is defined based on the experimental regression curve, stored in the AMR repository.

The layer number limit holds true also for the adaptive slicing. Unlike the uniform slicing, a simple repetition of a number of layers cannot be exclusively applied in the case of the adaptive slicing. Firstly, a layer prioritization policy needs to be defined to derive a list of critical layers. Sudden changes in the areas of subsequent layers of an ablation feature, high differences between the contour areas detected within the same layer or levels directly indicated by the user will define the positioning of the critical layers along the ablation direction. This list will be used during the adaptive slicing to define threshold height levels between integer numbers of passes following a bottom-up approach. By default, only one pass can be performed for every critical layer whereas a non-critical layer can be repeated multiple times in order to respect the layer limit.

Subsequently different infill strategies such as parallel and crosshatch, either unidirectional or bidirectional, can be applied to remove the material within the outer contour of each layer. For a parallel bidirectional strategy, the laser beam removes material back and forth along consecutive parallel linear tool path segments located at the hatching distance one from another. Once the scanning cycle of one layer is completed the Z-axis is lowered with the value of pre-defined layer thickness so the beam focus would be again on the next exposed surface. For a crosshatch bidirectional strategy, the area of a layer is ablated twice since the infill pattern consists of two sets of parallel lines with the second set being rotated with a specific angle with respect to the first one. For this strategy a factor of 2 will be applied to the layer thickness values extracted from the regression curve in Fig 2b.

In the last step the entire ablation strategy designed for the removal of the detected deviation will be translated into a part program to be run on the hybrid machine.

5. Case study

The aim of the hybrid manufacturing experiment is to test the capability of the proposed algorithm to generate an adaptive slicing strategy for the ablation of out-of-tolerance shape deviations. The correct removal of such geometric defects promotes an effective compensation for AM process deviations and the preservation of the part geometric quality across subsequent deposition steps.

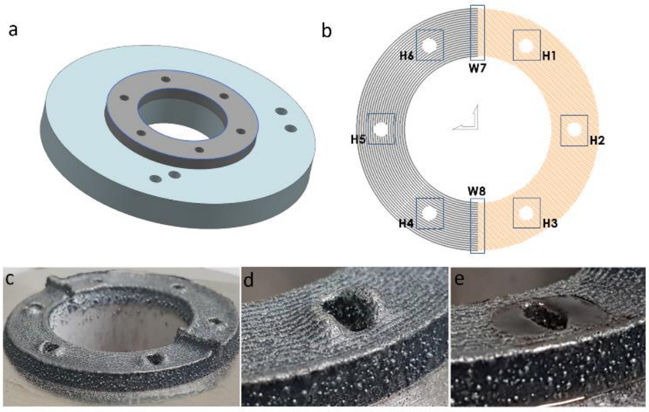

Fig. 4. (a) CAD of the disc part on flange; (b) deposition tool path strategy with two different patterns; (c) disc part with shape deviations; (d) deviation volume around hole H4; (e) overview of the ablated area around H4

The hybrid workflow initiates with the deposition of a 4 mm height disc-shaped part on top of a flange substrate (Fig. 4a). The CAD topology of the part features areas with fully dense material as well as an array of holes with the diameter d=3mm. The design of the geometry specimen jointly with the tool path strategies were defined with the intent of simulating the generation of two types of shape deviations. The first one addresses the over-sized volume of material around the contour of the holes (H1 to H6 in Fig. 4b). A second type of defect can be noticed in the interface area between the two tool path strategies (W7 and W8 in Fig. 4b). It takes the form of a wall-shaped feature and is the result of an excessive concentration of the start and end points of the tool path segments for the two aforementioned strategies. The deposition parameters are listed in Table 2.

The shape deviations are identified during the registration of the cloud of points issued from part 3D scanning with the nominal CAD followed by their extraction into two separate volumes. A first volume quantifies the material deposited in excess while the second one identifies the regions of the built with missing material.

The former volume will be promoted for the downstream processing. More specifically, the over-sized contour area of the hole H4 (Fig. 4d) is isolated to exemplify the adaptive slicing for ablation. Before the transformation of the deviation volume into machine code for the execution of the ablation process a number of preparatory activities are required.

Table 2. Deposition parameters

Laser power [W]	300
Laser spot[mm]	1
Axis speed [mm/min]	900
Hatching distance [mm]	0.468
Tool path patterns	Contour offset / Raster 0-90 deg
Layer thickness[mm]	0.2

Firstly, the separation and denoising of the cloud of points for the region of interest and definition of the bottom reference are performed (Fig. 5a). Ablation takes on the role of removing the excess material above a lower cutoff limit imposed on the cloud of points. The limit is established with respect to the Z coordinate of a plane fitted to the neighboring in-tolerance top surface of the built. All points below this bottom reference limit are discarded. Secondly the meshing, smoothing and slicing are carried out (Fig. 5b and Fig. 5c).

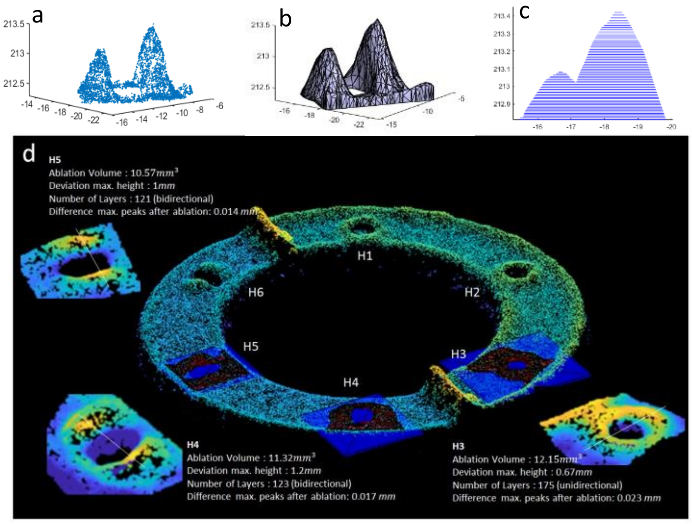

Fig. 5. (a) H4-Denoised cloud of points; (b) H4-Deviation volume (STL); (c) H4-closer view of the first slices to be manufactured with variable thickness; (d) Ablation details for deviations around H3-H5 holes

The geometry evaluation performed after the 1µm slicing allow us to characterize the shape of the deviation. Two opposite wall-like structures displaying a smooth width reduction from the base to the top are identified. The irregular shape of the deviation and the interpretation of the layer statistic values qualifies the adaptive slicing as the most suitable approach to discretize the entire volume. By running the algorithm, a total of 123 layers with variable thickness are generated for the removal of 11.32 mm^3 of over-deposited material (Fig. 5c). Since for this particular case the layer limit is not reached, the establishment of a layer manufacturing priority list is not necessary. Subsequently the infill tool path strategy for each layer is prepared considering a bidirectional crosshatch pattern and the same process parameters as depicted in Table 1. An overview of the adaptive slicing data for the first 48 layers is shown in Fig. 6.

The coordinates of the points resulted from the 3D scanning are used for both the identification of the Z bottom reference and the precise positioning of the areas of the as-deposited part requiring ablation to reach the targeted net shape. The positioning of the cutoff planes, the strategy proposed by the slicing algorithm as well as the outcomes of the ablation operation performed to remove the deviations around the H3, H4 and H5 holes are shown in Fig. 5d. The part program for the selective ablation is generated directly in the working coordinates defined for the previous deposition operation. The outcome of the ablation operation for H4 hole is shown in the Fig. 4e.

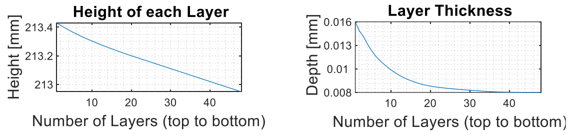

Fig. 6. Layer slicing information

6. Discussion

Understanding and controlling the ablation depth per pass is essential for the quality obtained at the end of the defect removal process. For ablation with nanosecond pulses the process is clearly thermal and dominated by classical beam-matter interaction [10]. The laser pulse energy will then be spread by heat conduction to an area outside the laser spot size causing the irradiated target to boil and evaporate. Upon the 3D scanning and analysis of the process outcomes the formation of a melt burr pattern could be observed at the interface between the ablated and as-deposited surfaces respectively. The burr formation could be explained by general phenomena associated with the ablation mechanism (e.g. surface ripples due to shock waves, ejected molted material and surface debris) but also by the heterogeneous distribution of layer thickness values across the deviation volume. The employment of identical process conditions in previous tests for the ablation of regular cavities with constant layer thickness displayed a minimum amount of burr. Although the underlying mechanism of the burr formation is not fully understood its presence is not critical for the subsequent deposition operations. Peak-to-valley measurements revealed an average height of one order of magnitude lower than the 1mm spot diameter of the deposition laser. Chemistry material responses, cumulative changes in the target material's surface texture and morphology will occur due to surface melting and a combination of ablation and thermally activated processes.

In addition to the thermal aspects the quantity of material removed per pass depends also on the performance of the laser scanner in relation to the variable area of the ablated layers. The timing difference between the fast on/off switching of the laser and the slower transient regimes of the galvanometer scanner will result into slower spot motions in the initial and final sections of each laser vector path.

For very small areas the laser vectors are extremely short and the scanner mirror's rotation operates only with acceleration and deceleration phases. The generalized concept behind the setting of an adaptive layer thickness is that the focus of the laser beam depends on the set depth of cut value correlated with the calculated area of the layer. The material removed by ablating 123 layers massively reduced the deviation and improved the surface quality around the hole. However, the final surface was subject to flatness defects.

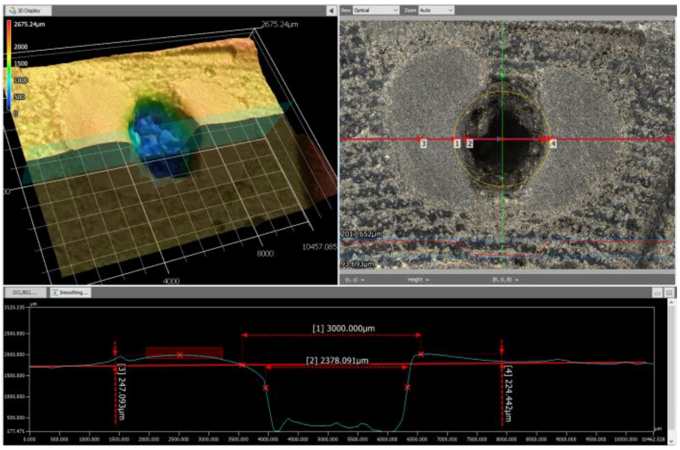

Fig. 7. Overview of the ablated area

The difference between the maximum peaks resulted after the ablation of both wall shaped deviations with respect to the bottom reference was estimated at 0.017mm (Fig. 7). One major concern is the focused distance and actual depth of cut, which go on changing nonlinearly with an increase in the area of the layers. One possible solution to improve the flatness would be the sequential ablation of the wall shaped deviations.

The ablation revealed also a significant deviation from circularity for the profile of the hole. This is the mere result of the insufficient dimensional accuracy of the contour offset strategy. By considering the profile of the manufactured hole inscribed in a circle with a diameter of 3mm (Fig. 7) the removal of excess material by ablation could be envisaged to control the hole's cylindricity. Due to the limited optical accessibility of machine's embedded 3D scanner and the missing of accurate data to describe the internal topology of the hole the execution of the ablation according to the proposed workflow is currently impossible.

7. Conclusion and future work

In this work we introduced an adaptive slicing algorithm for the post-processing of LMD-generated Inconel parts based on an empirical regression model characterizing the dependency of the material removal rate on the ablated layer area. The approach combines the advantages of an integrated hybrid process chain consisting of laser-based additive and subtractive technologies and in-process inspection for the consistent manufacturing of 3D shaped geometries. The integrated hybrid workflow enables the removal of irregular shape deviations through nanosecond ablation which can be deployed either at the end or recursively at different stages during the deposition of a part. The selective ablation reduced the height of an irregular deviation detected on a deposited sample by at least 80%, significantly minimizing the risk of deviation propagation across subsequent deposition operations. However, the bottom of the ablated surface was subject to lack of planarity and additional tests considering the sequential ablation of distinct deviation features will be conducted to address this issue. Furthermore, since the material removal rate depends also on the absorbed energy by the target material, the concept needs to be validated with additional materials. More scientific experimental work is needed as well to evaluate the correlation between the shape and area of ablated layers with respect to different ranges of operating parameters.

With an average material removal rate of 0.76 mm^3/min the performance of the ablation process is rather low in comparison with conventional machining. Consequently, the efficient use of laser ablation in a laser-based hybrid manufacturing workflow is mainly justified by the selective removal of limited irregular shape deviations of AM parts and the realization of high-resolution features on difficult-to-cut materials.

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