

SURFACE ROUGHNESS OPTIMIZED ALIGNMENT OF PARTS FOR ADDITIVE MANUFACTURING PROCESSES

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Abstract

The layered structure of Additive Manufacturing processes results in a stair-stepping effect of the surface topographies. In general the impact of this effect strongly depends on the build angle of a surface, whereas the overall surface roughness is caused by the resolution of the specific AM process. The aim of this work is the prediction of the surface quality in dependence of the building orientation of a part. These results can finally be used to optimize the orientation to get a desired surface quality. As not every area of a part can be optimized, a predetermination of areas can be used to improve the surface quality of important areas. The model uses the digital STL format of a part as this is necessary for all AM machines to build it. Each triangle is assigned with a roughness value and by testing different orientations the best one can be found. This approach needs a database for the surface qualities. This must be done separately for each Additive Manufacturing process and is shown exemplary with a surface topography simulation for the laser sintering process.

Introduction

Additive Manufacturing (AM) processes directly produce a real part from a computer-aided design (CAD) file without the need of a tool. The CAD part has only to be saved as a STL (standard triangulation language) file and sliced into two dimensional layers of about 20 μm to 300 μm (depends on machine and process). The assignment of the spatial position in the building chamber and support structures (if needed) are done with machine specific software. In general, raw material is treated or deposited layer-by-layer at the cross section of a part and the building platform lowers each cycle by one layer thickness and material is allocated again. The first commercial process stereolithography (SLA) utilizes photopolymers by curing it with ultraviolet laser. Raw materials can also be powders of polymers, metals and ceramics for processes like selective laser sintering (SLS), selective laser melting (SLM) and electron beam melting (EBM), where the powder is melted by a laser or electron beam. Different from these processes the fused deposition modeling (FDM) uses extruded filaments to deposit layers [1, 2].

The layered structure of all AM processes leads involuntarily to a stair-stepping effect on part surfaces which are tilted in respect to the building platform. Additionally, some processes need support structures to attach the part to the building platform, sustain overhangs or dissipate heat, where residues of removed support structures on the surface are present and deteriorate the surface quality. These effects depend strongly on the orientation of a part surface inside the building process. Hence, the orientation of a whole part has a big influence not only on the resulting surface quality. Also the accuracy of part details and the building time and costs due to the build height are important factors, too [3].

State of the art

Some work was done in the past years to determine optimized build orientations regarding various target values for different AM processes. Reeves and Cobb presented a surface roughness prediction for layered manufacturing (LM) to optimize the building direction in terms of overall surface roughness for given parts [4]. In particular they focused on the SLA technology, which is based on the photopolymerization of liquid resin, therefore having smaller surface roughness as in SLS. Hence, they could express the mean roughness index (R_a) as a function of surface angles only by stair-stepping effect. This distribution was compared with experimental data from surface angles from 0° to 180° in 3° intervals. These measurements were done with parts from SLA, SLS and FDM processes. For SLS parts the results showed no correlation between the theoretic distribution and the measured roughness for surface angles between 90° and 180° , meaning surfaces whose surface normal are directed to the bottom. The independence of the stair-stepping effect in this case is caused by the filleting effect Bacchewar et al. described in their work [5]. Cheng et al. had a multi-objective approach to derive the optimal orientation for SLA [6]. They considered mainly part accuracy and building time, where part accuracy is a weighted factor for several types and features of surfaces. Alexander et al. focused on the build costs considering build height and time as well as volume of material and support material for SLA and FDM processes [7]. In addition to this they also derived the prebuild and post processing cost including support removal and finishing time, again comparing different orientations of a part to determine the optimal one. Expanding to this Xu et al. investigated additionally SLS and LOM processes in terms of building costs as the major optimization objective while considering building time, accuracy and surface finish as secondary objectives [8].

A more detailed approach on optimizing the orientation regarding part accuracy can be found at Lin et al. and Masood et al. [9, 10]. They examined the volumetric errors which occur due to the layered structure and part approximation through

the STL file format in SLA, FDM and LOM processes, where the stair-stepping effect dominates the surface topography. Tilted and round surfaces are built as stair steps and the volumetric difference to the CAD file can be computed and minimized by rotating the part.

Another advanced work for reducing computational effort were done by Canelidis et al. and Phatak and Pande [11, 12]. They apply optimization algorithms on SLA and SLS process, respectively. A genetic algorithm with build time and part quality as the main optimization criteria is used to find an optimal orientation for a part in a shorter computational time.

Although a few attempts were done in the past on automation tools for an optimized build orientation for AM, the standard procedure is still dominated by manually packing and rotating parts for build jobs. This work starts with a surface topography simulation of SLS parts, which is more complex than the other aforementioned processes FDM, SLA and LOM as the raw material is powder. This prediction of surface roughness is then used to find the optimal build orientation regarding surface quality.

Basics

In the early years of AM, Frank and Fadel set up the first simple tool for selecting an optimal orientation for parts in the SLA process [13]. They already identified a lot of factors which are influenced by changing the build orientation of a part in AM processes. The surface finish is one of the most important properties which can be optimized and is considered in nearly any work. The stair-stepping effect occurs for all AM processes and can be described by the building direction, though the detailed geometry of the layer edges can differ in the various processes. This effect impairs also the part accuracy, especially tilted and round surfaces are approximated to a greater or lesser extent in comparison to the CAD surface where the layered structure as well as the STL file format are an issue [9, 10]. Another obvious factor, which can be varied through rotation of a part, is the z-direction height respective the build height. The build height is proportional to the build time and the needed raw material in the process and therefore also proportional to the costs of the building process. As the material in some AM processes can be reused only the solid material volume of a part has to be taken into account there. However the volume of support structures (depend on AM process) has to be considered not only for calculating the building process costs. More amount of support structures deteriorate the surface finish of the supported surfaces and require more time to remove it from the part which condense again in costs of the post-process [7, 8]. A factor becoming more important is the mechanical resilience of parts as AM processes move on from rapid prototyping to direct manufacturing

and series production. These mechanical properties show anisotropic behavior due to the layered structure, meaning an optimized orientation regarding the load axes of a part can be useful, too [12].

Simulation of the surface topography

The topography of LS part surfaces depends on two main effects, namely the stair-stepping effect due to the layered structure and the adherence of incomplete melted particles on the surface due to the molten bath inside the powder bed [14]. The effect of stair-stepping strongly depends on the layer thickness d and the build angle θ with respect to the building platform. Additionally, it is important whether a surface is directed to the top or bottom, also known as upward or downward directed surfaces, respectively [5].

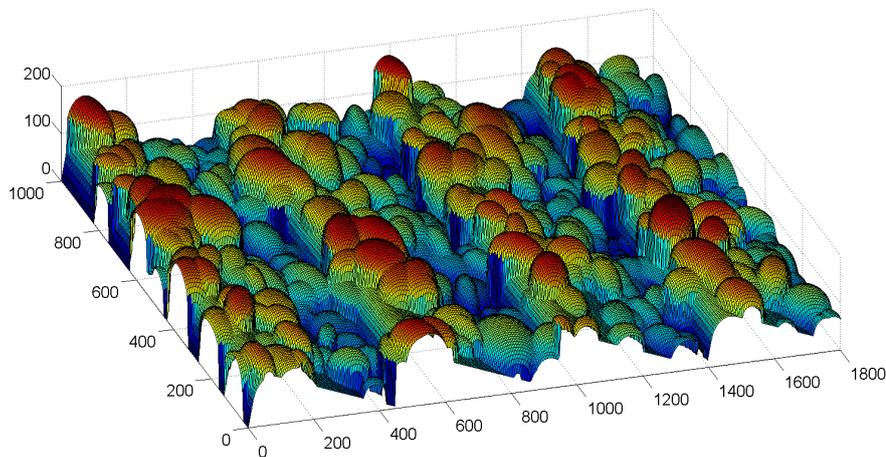


Figure 1: Assembled simulation of both effects to total surface topography with $\theta=15^\circ$, $dop=5 \mu\text{m}$ and $P(x)=0.007$.

The simulation of adhered particles depends on some other parameters. First of all, the particles have a specific size distribution DP and morphology. Further on they are allocated with a spatial distribution or density on the surface. The last parameter that must take into account is the amount of adhesion, meaning how much of the particle protrudes from the surface. The creation of particles in the model is limited to one layer on the surface. This is because of the standard practice of shot-peening parts with glass beads and therefore removing all low adhered particles.

As this simulation runs on MATLAB there are some limiting conditions. Overhangs cannot be expressed as every point in the matrix can only contain one value

with height information. Also the size corresponding to the field of view (unit is μm) and density of points has to be defined for each simulation, meaning the resolution associated with computational time can be easily varied. The density of points is given by the distance of points dop , which is the same in x- and y-direction. In the first stage of the simulation the two main effects are modeled separately. The stair-stepping effect depends on θ and d . θ can vary between 0° and 180° , defining 0° to 90° as upward directed and 90° to 180° as downward directed surfaces.

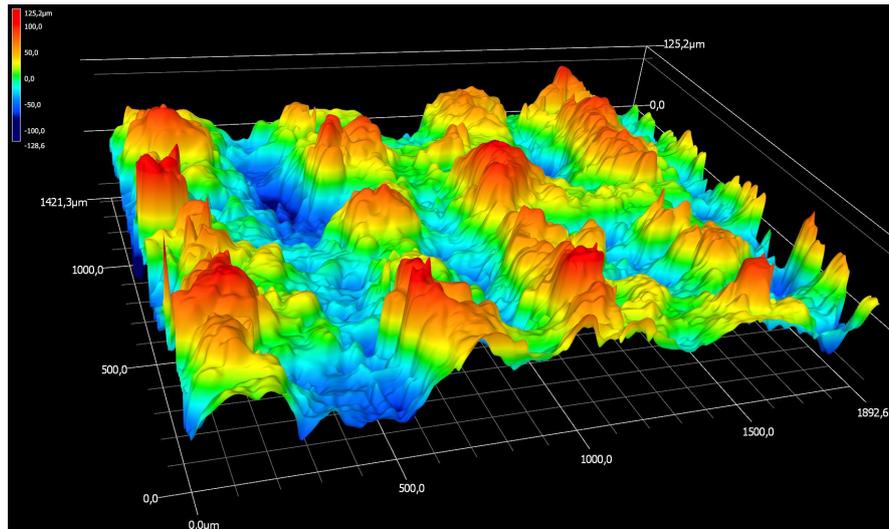


Figure 2: 3D optical measurement of a real LS part surface with $\theta=15^\circ$, the field of view is approx. $1900 \times 1400 \mu\text{m}^2$

The part of simulating the adhered particles includes the above mentioned parameters size distribution DP , morphology, spatial density and degree of protrusion. For now the size distribution was assumed to be the one of the raw material. This distribution was measured by laser diffraction method of the nylon material "PA 2200" from EOS GmbH. Also the morphology was evaluated by image analysis of dispersed powder. The particles have the shape of ellipsoids with a mean aspect ratio of 0.72 and are arranged in a random orientation. The spatial distribution is implemented through a probability $P(x)$ of creating a particle on a point of the basic mesh. As a planar surface is simulated the y-direction only enlarges a 2D-profile of the steps why only in x-direction perpendicular to the steps a spatial distribution of the probability is expected. The degree of protrusion is implemented with another distribution DZ , which shifts the center of a particle above and below the plane. Figure 1 shows the total surface topography after assembling the two effects together using the example of a 15° tilted surface. As a

comparison a measurement of a real part surface can be seen in Figure 2. A more detailed explanation of the simulation can be found in our previous work [15].

Optimization of part alignment

In correlation with experimental results the topography simulation yield in a database of roughness values for LS part surfaces of 0° to 180° build angle. In the next step this database is taken to optimize the alignment of a part inside the building chamber regarding surface quality and build height.

The optimization tool is set up in MATLAB and the basis is provided by a STL file of a CAD part. This file format contains the geometric information of each triangle the part is approximated with, particularly all vertices and normal vectors. The normal vectors are then used to calculate the build angle of each triangle in respect to the building platform. With the knowledge of the build angle each triangle is assigned with a roughness value to determine the initial state. Then the optimization starts by rotating the normal vectors around the x- and y-axis in discrete steps and repeating the assignment each time.

The target value used for surface quality is the mean roughness depth R_Z [16]. An area weighted average of the whole part is calculated as follows:

$$\overline{R_Z} = \frac{\sum_i^N A_{\Delta,i} \cdot R_{Z,i}}{\sum_i^N A_{\Delta,i}} \quad (1)$$

with N the number of triangles and $A_{\Delta,i}$ the area of each triangle, which is calculated by the given vertices. Finally the smallest value of $\overline{R_Z}$ indicates the optimal orientation of the part.

Some parts have geometric features which process-related need to be aligned in a specific direction to get the best accuracy. For example, should the axis of a linear hole lie parallel to the build direction to receive no stair-stepping inside the hole. For such parts it is possible to determine a specific axis or some different ones for a more complex part to manually compare the resulting surface quality.

As a secondary optimization objective, the build height of the part is considered. For each optimization step the build height is displayed and the user can decide, which combination of surface quality and build height suites his requirements.

Demonstration with test part

Hereafter the demonstration of the tool functions is revealed using the example of a side mirror model which is shown in Figure 3 from two point of views [17]. The large plain surface, which is oriented vertically in the left figure, is the area where a mirror must be implemented after building this part in polymer material.

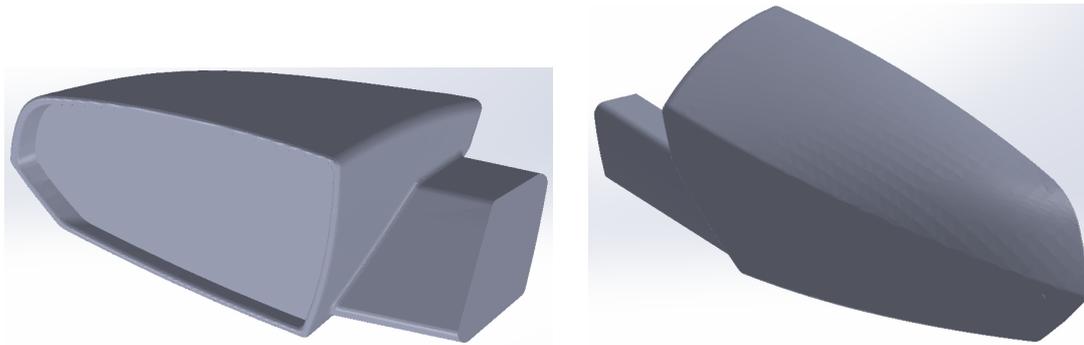


Figure 3: CAD model of an automotive side mirror from the front (left) and back (right) side

To demonstrate how different orientations affect the surface quality, Figures 5 and 6 feature depictions of the found orientations with the lowest and highest $\overline{R_Z}$, respectively. The initial orientation is shown in Figure 4 which is simultaneously the orientation with the smallest possible build height of 112.6 mm for this part. The orientation with a rotation of $[180^\circ, 90^\circ]$ around x- and y-axis has the lowest $\overline{R_Z}$ of 101 μm and a build height of 277.6 mm whereas the orientation with a rotation of $[40^\circ, 15^\circ]$ has the highest $\overline{R_Z}$ of 124 μm and a build height of 134.7 mm. Hence, the averaged surface roughness can vary about 25 %.

Finally, the potential of defining specific areas of a part for optimization will be shown. As the large plain surface will not be visible in the application of the part because a mirror must be implemented the surface quality of this area can be poor. Therefore, the triangles of these area were manually deleted and the optimization tool was run again. The result is shown in Figure 7. The $\overline{R_Z}$ of the calculated optimal orientation ($[175^\circ, 120^\circ]$) amount to 106 μm with a build height of 285.1 mm. In comparison with the lowest $\overline{R_Z}$ orientation above these values imply no improvement for the part. But without considering the triangles of the plain surface for above mentioned lowest $\overline{R_Z}$ orientation the $\overline{R_Z}$ value is deteriorated to 103 μm , whereas the consideration of the missing triangles amount to a $\overline{R_Z}$ value of 102 μm . Hence, the visible areas of the part get a better surface roughness which can notably be seen in the figures where the lowest $\overline{R_Z}$ orientation shows high surface roughness indicated in orange at the top of the part.

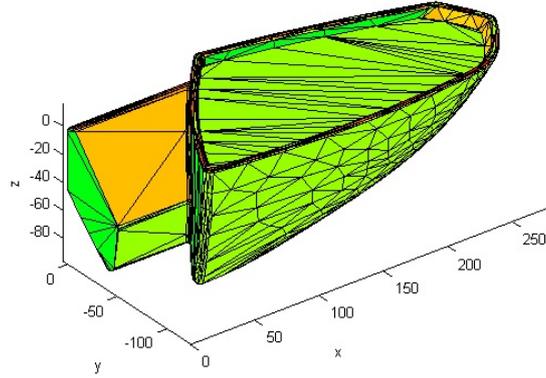


Figure 4: Initial orientation of the demo part before calculating the optimal rotation

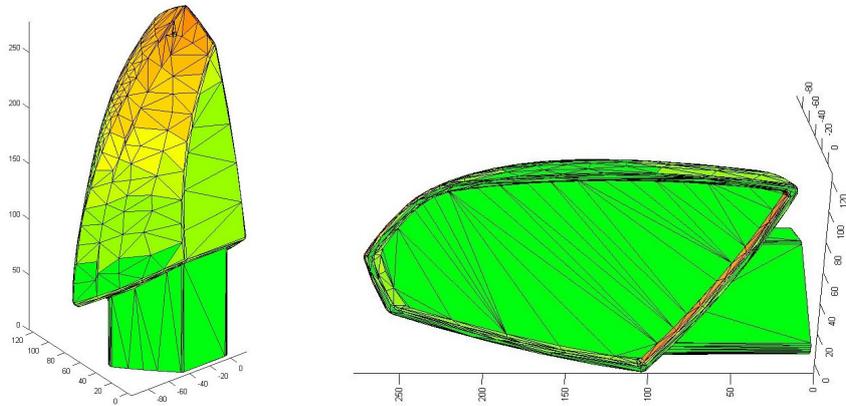


Figure 5: Depiction of the build orientation with minimal $\overline{R_Z}$ (left) and the point of view from the front side (right). The colors indicate the surface roughness R_Z from 90 μm (green) to 188 μm (red).

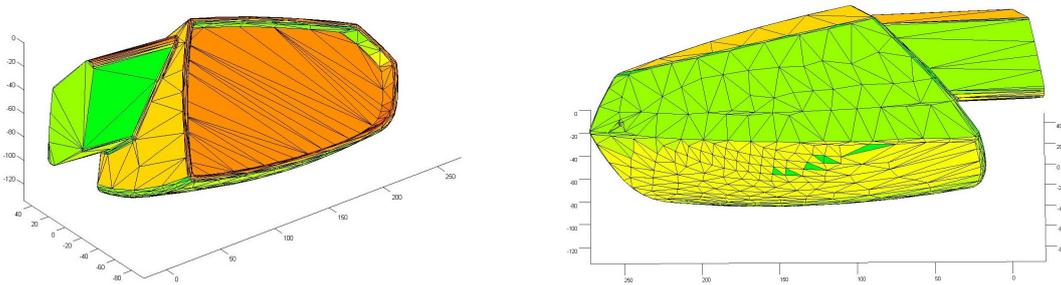


Figure 6: Depiction of the build orientation with maximal $\overline{R_Z}$ (left) and the point of view from the back side (right).

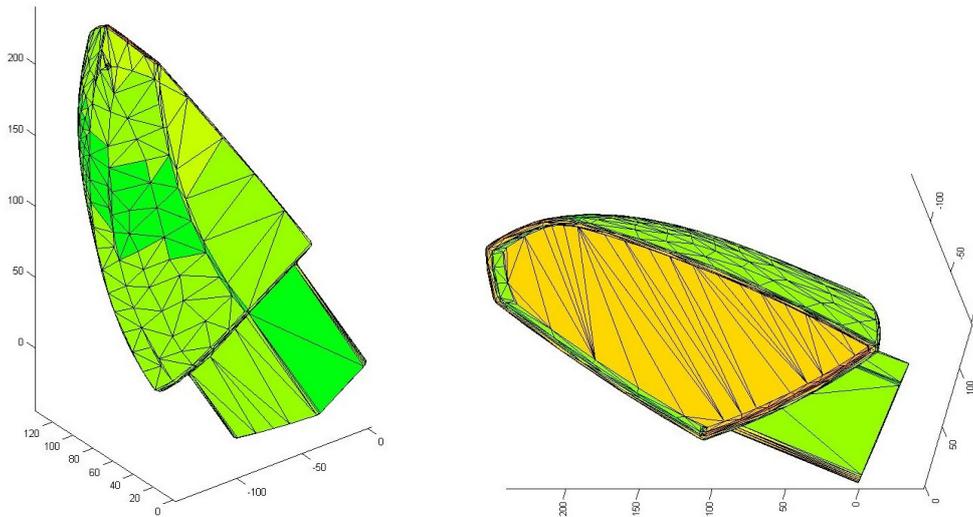


Figure 7: Depiction of the build orientation with minimal $\overline{R_Z}$ without considering the plain surface of the part (left) and the point of view from the front side (right).

Summary and Outlook

An alignment optimization tool for AM processes which uses surface roughness and build height as optimization objectives was presented. The previous surface topography simulation of the LS process sets up the surface roughness database for the optimization tool. Using the example of a demonstration part the function of the tool is shown and the resulting optimization potential regarding surface quality and build height can be seen. Especially the results for the surface quality of a part lead to the general assumption that the orientation of a part affects the overall part surface roughness in a range of 25 %.

In terms of extending the capabilities of the tool, the AMF (Additive Manufacturing) file format will be implemented. The AMF format can save more information of a part, for example color or material. This possibility will be used to select certain areas of a part and mark them. With the help of marking different areas can be treated in other ways, for example this gives the possibility to select visible areas of a part so that these areas can be optimized to a best possible surface quality. This can also give the opportunity to decrease the build height while maintaining a good surface quality.

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