

# **Simulation of the Surface Topography on Laser Sintered Polymer Parts**

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## **1 Abstract**

One barrier of laser sintering (LS) to become the main process for Direct Manufacturing (DM) is the surface quality of LS parts. Hence, the property which has to be improved is the rough surfaces of LS parts due to the layered structure. Another additional effect is the incomplete melting of powder particles on the surface due to the high process temperature. In this paper we demonstrate our approach of a theoretical model for the topography of LS part surfaces.

We investigated the surface roughness as a function of surface orientation. Considering that the model involves further variables as layer thickness, particle density and particle size distribution to describe the topography precisely. Experimental results were used to optimize and check the results of the model.

## **2 Introduction**

Laser sintering is a technology to directly produce a real part out of a computer-aided design (CAD) file without the need of a tool. The CAD part has only to be saved as STL (standard triangulation language) file and sliced into layers of 60 – 180 µm. The assignment of the spatial position in the building chamber is done with machine specific software. This file contains now all the information, which is needed, to build up the part layer-by-layer. The raw materials that are used in LS are powders of different materials like polymers, metals and ceramics. In general, reservoirs with powder provide the amount of material needed for one layer, which is then allocated by a counter-rotating roller or blades (depends on machine system). Then the powder is heated up, in the case of polymers, to a few degrees under the melting temperature of the material, so that a CO<sub>2</sub> laser scans and melts the required area of this specific layer to build up the part. The unmelted powder remains and functions as support. Finally, the building platform is lowered by the thickness of a layer and these steps are repeated until the part is complete [GTH12].

This layered structure leads automatically to a stair stepping effect on part surfaces which are tilted in respect to the building platform. On top of this the process causes an incomplete melting of nearby particles to the surface. For the surface topography and especially the roughness imply these effects that they depend on the orientation in the building chamber. Hence, a theoretical model which can predict surface roughness gives essential information without building a part and measuring it. Furthermore it could help improving a parts surface quality by finding the best orientation in the building chamber. As such a specific model doesn't exist this work establishes the first detailed model for simulating part surfaces in the LS process.

The model simulates the topography for a flat part surface, meaning for one building angle. This is done with the program MatLab and set up in two stages. First, the stair stepping and the incomplete

melted particles are simulated individually with their specific properties, which are explained later on. Then the two surfaces are summed up to the final surface topography. From this topography roughness values can be calculated according to comparable experimental data.

### 3 State of the Art

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 [RC97]. In particular they focused on the stereolithography (SL) technology, which is based on the photopolymerization of liquid resin, therefore having smaller surface roughness as in LS. 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  $0^\circ$  to  $180^\circ$  in  $3^\circ$  intervals. These measurements were done with parts from SL, LS and fused deposition modeling (FDM) technologies. For LS parts the results showed no correlation between the theoretic distribution and the measured roughness for surface angles between  $90^\circ$  and  $180^\circ$ , meaning surfaces whose surface normal are directed to the bottom. The independency of the stair-stepping effect in this case is caused by the filleting effect Bacchewar et al. described in their work [BSP07].

An experimental quantification of surface quality for LS with polycarbonate (PC) material was done by Tumer et al. [TTW+96]. They established a regression model and measured 2D tactile profile scans on PC parts and take a power spectrum from the data. With the results of this method they can quantify the influence of surface deviations brought in by faults within the process. Specific appeared frequencies in the power spectrum represent specific influences like layer thickness, roller vibration and laser beam scan lines.

### 4 Basics

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 [TTW+98]. The effect of stair-stepping strongly depends on the layer thickness  $d$  and the build angle  $\theta$  with respect to the building platform. Additionally it's important whether a surface is directed to the top or bottom, also known as upward or downward directed surfaces, respectively. The mentioned filleting effect of downward directed surfaces leads to different modeling of the stair-stepping effect.

The simulation of adhered particles depends on some other parameters. First of all the particles have a specific size distribution  $D_P$  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 on 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.

## 5 Simulation Model

As we work with MatLab for this simulation there are at first some limiting conditions we want to point out. Overhangs cannot be expressed as every point in the matrix can only contain one value with height information. Also we have to define the size corresponding to the field of view (unit is  $\mu\text{m}$ ) and density of points 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  $d$  and  $\theta$ .  $\theta$  can vary between  $0^\circ$  and  $180^\circ$ , defining  $0^\circ$  to  $90^\circ$  as upward directed and  $90^\circ$  to  $180^\circ$  as downward directed surfaces. In figures 1 and 2 the different approaches for upward (figure 1) and downward directed (figure 2) surfaces are shown. Modeling the upward directed steps a triangle shape is used, where the sharp edge is replaced by a pitch circle with radius  $d/4$ . The value of the radius is an approximation due to the fact that the surface tension of the molten material is not known and we cannot measure it inside the process, but this should be more realistic than a sharp edge. This modified triangle can then be expressed by three different functions for each section, respectively. For downward directed surfaces the shape of the spatial distributed laser beam under the powder bed surface is taken into account. This leads in our approximation to a stringing together of pitch circles with a radius of  $2d$ , which comes from the correlation that the penetration depth of the laser according to several parameters as energy density, laser power, thermal conductivity etc. is assumed to be approximately that value [Bac97][GS07]. This assumption has to be validated.

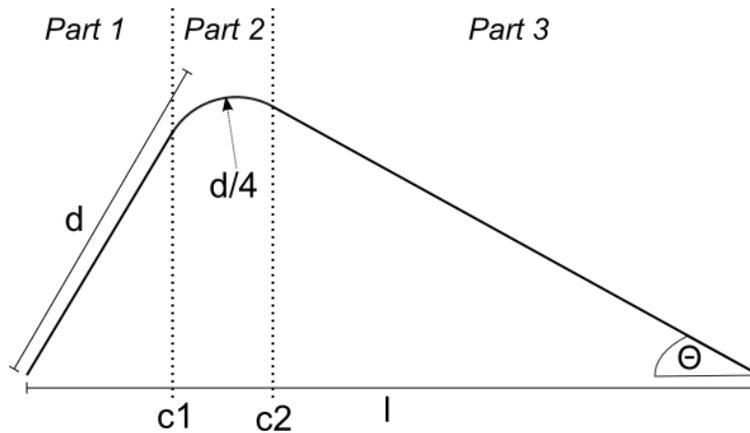


Figure 1: Sketch of the approach to model upward directed surfaces.

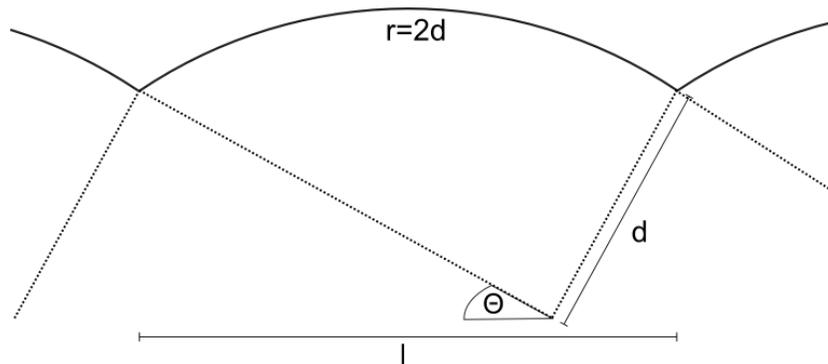


Figure 2: Sketch of the approach to model downward directed surfaces.

Following figures illustrate the simulation model of the stair-stepping effect both for upward directed (figure 3) and downward directed (figure 4) surfaces at a build angle of  $\theta=15^\circ$  and  $\theta=165^\circ$ , respectively.

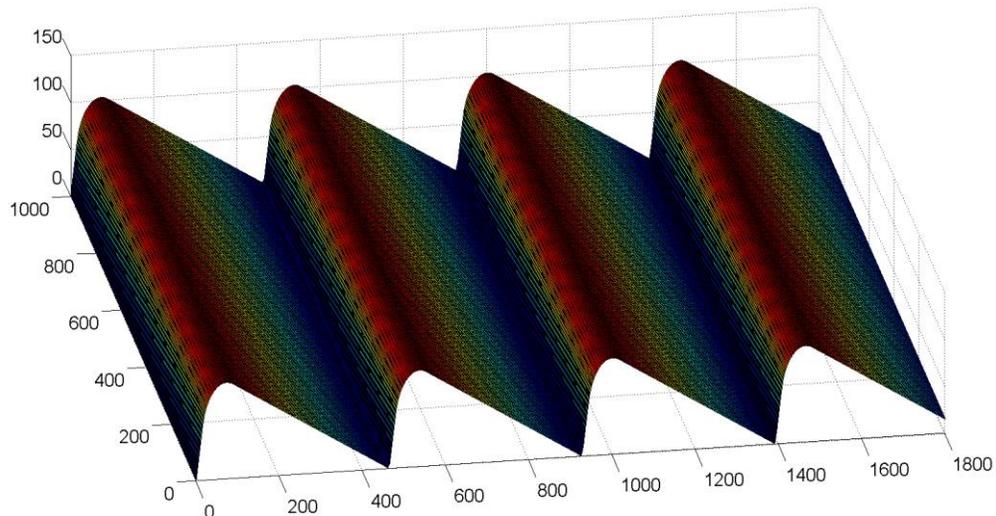


Figure 3: Simulation of the upward directed stair-stepping effect for  $\theta = 15^\circ$ .

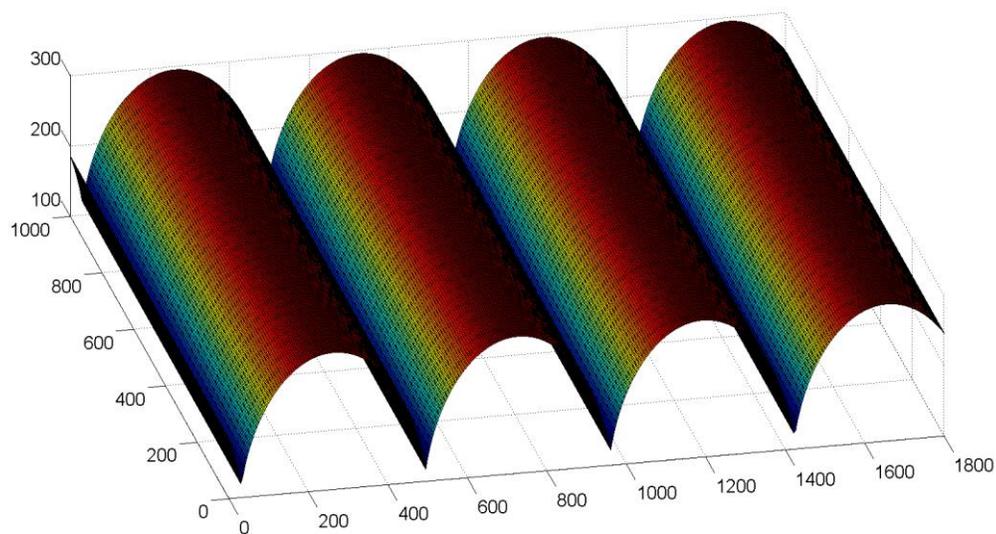


Figure 4: Simulation of the downward directed stair-stepping effect for  $\theta = 165^\circ$ .

The part of simulating the adhered particles includes the above mentioned parameters size distribution  $D_P$ , morphology, spatial density and degree of protrusion. For now the size distribution was assumed to be the one of the source material. This distribution was measured by laser diffraction method of the PA12 material “PA 2200” from EOS GmbH. Also the morphology was evaluated by image analysis of dispersed powder and is included already. The particles have the shape of ellipsoids with a mean aspect ratio of 0.72. The orientation of them on the surface is random. In detail the spatial density and degree of protrusion depend on the process parameters

the part was built with, e.g. different energy density for different layer thicknesses will lead to another adhesion behavior of the particles. The spatial distribution is implemented through a probability  $P(x)$  of creating a particle on a point of the basic mesh. As we simulate a planar surface 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  $D_z$ , which shifts the center of a particle above and below the plane. A resulting model is shown in figure 5, where the different sized, random orientated particles with different protrusions can be seen. The density of particles is created by an probability  $P(x)=0.007$  at an image size of  $1800 \times 1000 \mu\text{m}^2$  with  $dop=5\mu\text{m}$ .

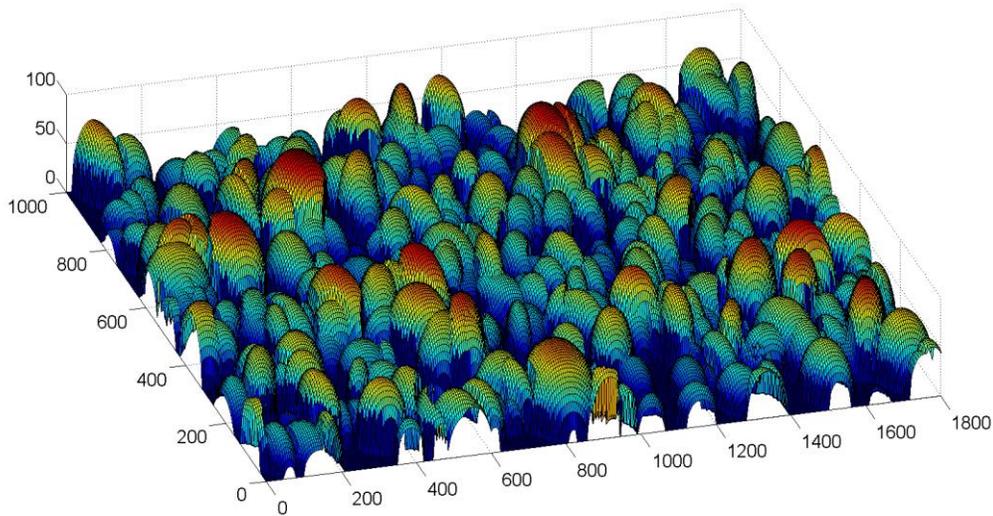


Figure 5: Simulation of the particles with  $dop=5\mu\text{m}$  and  $P(x)=0.007$ .

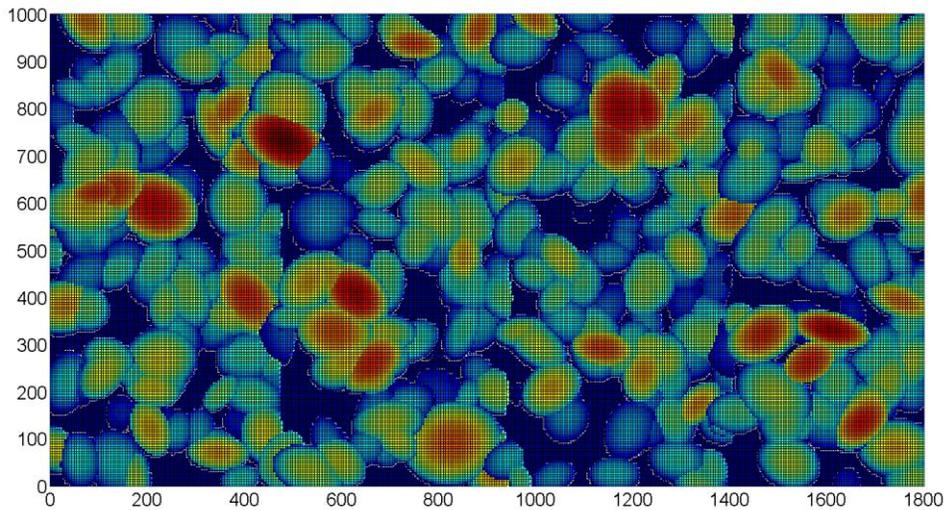


Figure 6: Top view of simulation with  $\theta = 15^\circ$ ,  $dop=5\mu\text{m}$  and  $P(x)=0.007$ .

In figure 6 the simulated particles can be seen in a top view of the simulation. The positions of particles and the orientation in x-y-plane are randomly distributed. Also different shapes distributed around the mean aspect ratio of 0.72 can be seen. Figure 7 then shows the total surface topography after assembling the two effects together.

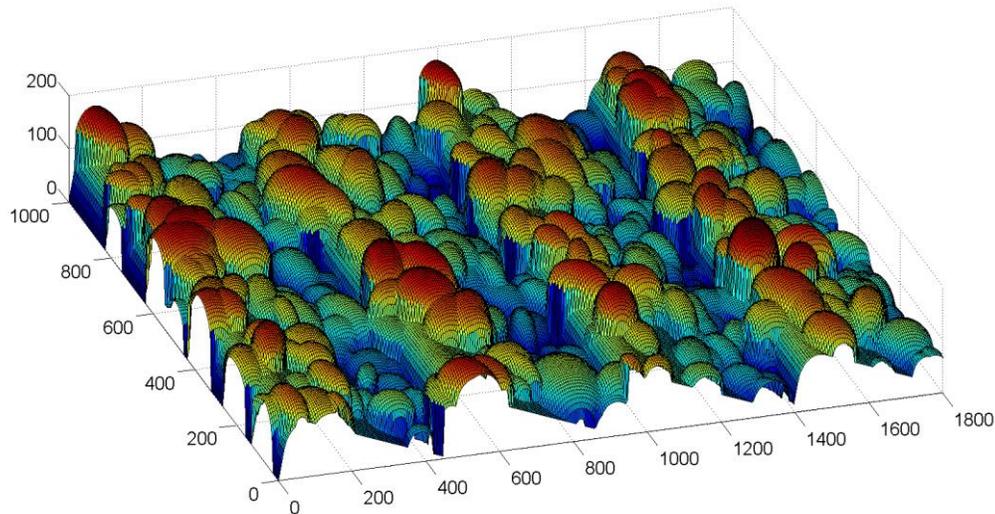


Figure 7: Assembled simulation of both effects to total surface topography with  $\theta = 15^\circ$ ,  $dop=5\mu m$  and  $P(x)=0.007$ .

## 6 Experimental Validation

The several input parameters of the simulation are not fixed and some of them will vary according to process parameters a LS part was built with. A qualitative relation can be done by measuring the surface with a 3D optical surface measurement system. Figure 8 shows a measurement of comparable field of view as simulated topography above, taken with “3D Macroscope VR-3100” of Keyence. The size of the steps fit to the simulated ones. The particles in the measured topography are not that isolated as they are in the simulation and the surface of them is not that smooth.

A quantitative relation was done with the analysis of roughness values  $R_a$  (arithmetical mean deviation) and  $R_z$  (averaged roughness) [DIN][ASME]. The experimental values were measured with a profilometer “Hommel Etamic T-8000” of Jenoptik. For each  $\theta$  the roughness values of twelve samples were determined, three line scans each. As the single measured length  $lr$  for these measurements are 4 mm the simulation was run with a size of  $4000 \times 250 \mu m^2$ . With  $dop=5\mu m$  the simulation consists of 50 lines perpendicular to the steps. For each line the roughness values were calculated and a mean value generated. This was done five times for each angle with the aim of fitting the roughness values to experimental data by adjusting die probability  $P(x)$ . The resulting probabilities varying between  $P(x)_{15^\circ} = 0.007$  and  $P(x)_{75^\circ} = 0.0085$  for build angles between  $15^\circ$  and  $75^\circ$ . The measured and calculated roughness values can be seen in figure 9.

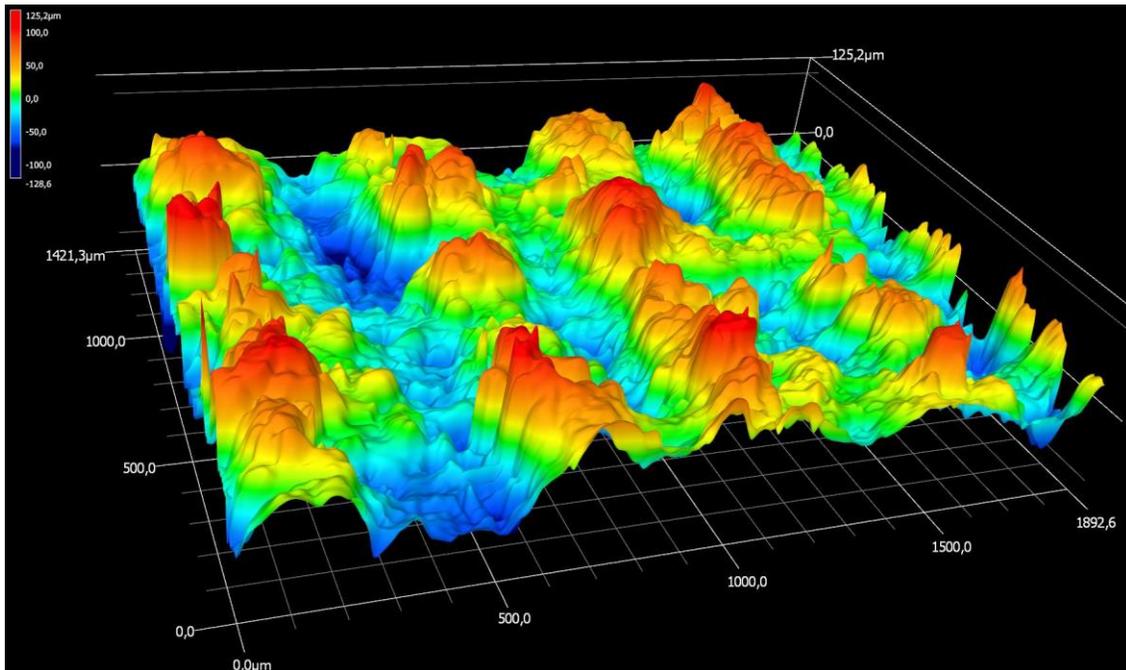


Figure 8: 3D optical measurement of a real LS part surface with  $\theta = 15^\circ$ , the field of view is approx.  $1900 \times 1400 \mu m^2$

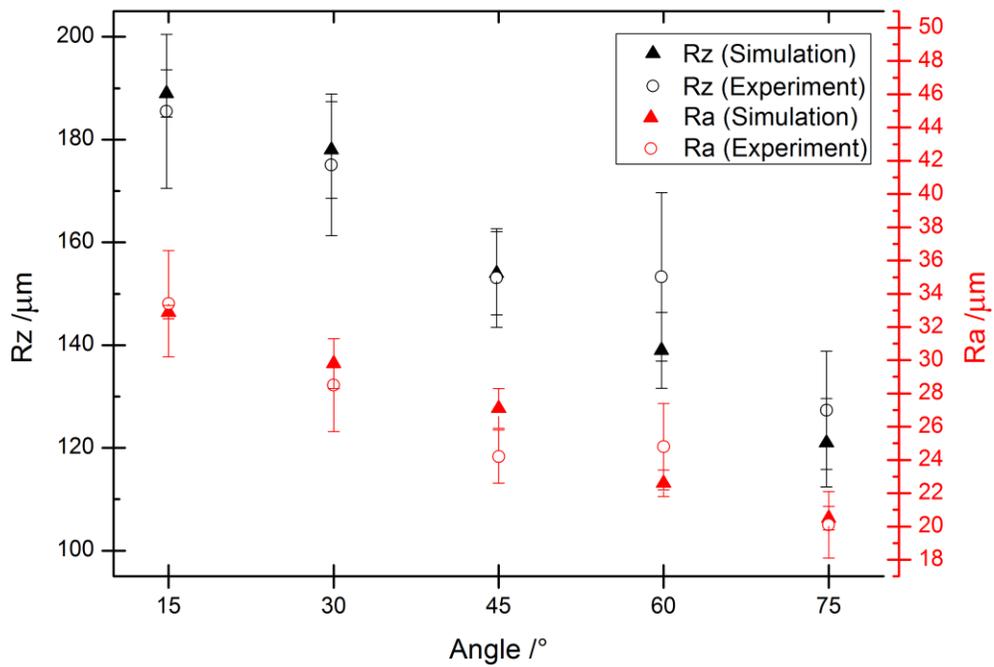


Figure 9: Roughness values of real LS parts and the simulation for different build angles.

## 7 Summary and Outlook

In the presented work a simulation model for the surface topography of laser sintered parts has been developed. The detailed consideration of the stair-stepping effect in combination with the adherence of incomplete melted powder particles is new in the field of polymer laser sintering. The exhibited simulation model operates in two stages. First, the stair-stepping effect is simulated according to the layer thickness  $d$  and the build angle  $\theta$ , considering different approaches for up- and downward directed surfaces in the building process. Separately the adhered particles are simulated by size distribution  $D_P$ , morphology, spatial density and degree of protrusion. Then these two effects are assembled together to the total surface topography. The size distribution and morphology is incorporated with the properties of the source material "PA2200". Qualitative and quantitative validation was also shown by 3D optical measurements and relation of roughness values  $R_a$  and  $R_z$ .

With the relation of the roughness values first assumptions for the spatial density of the particles were done. With the help of extensive 3D topography measurements on real part surfaces this parameter will be validated and maybe extended to a direction distributed parameter, as different particle densities e.g. at edges are conceivable. Such measurements will also be necessary to determine the degree of protrusion and the particle size distribution on the surface. Additionally all parameters will be evaluated for part surfaces built with different process parameters, e.g. layer thickness, energy density etc. to get a topography prediction tool for LS parts.

## 8 Acknowledgement

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