Simulation of mid-spatials from the grinding process

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This paper focuses on the simulation of the creation of mid-spatial frequencies (mid-spatials) during the grinding process of optical components. The goal is to simulate this generation process and determine the correlating grinding parameters for mid-spatials. On this base, grinding parameters which lead to less mid-spatials could be determined.
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1 INTRODUCTION

The mid-spatial frequency errors (MSF errors) are a well-known problem in the manufacturing of optical components, especially in the grinding process. Errors within this range are hard to correct and can cause great effort to reach the specified surface quality. Therefore there are a lot of different strategies to avoid the creation of MSF errors e.g. [1]–[3].

This Paper introduces a new approach to control and avoid the generation of MSF errors. This approach is based on a virtual simulation and therefore the costs to implement it into an existing manufacturing process are very low. Furthermore it is possible to determine the result of the grinding process without using real material or machine time.

The goal of this research project is to provide a simulation software tool which can predict the resulting surface structure of a grinding process. On this base the grinding parameters can be optimized until certain parameters are determined, which lead to the least creation of the critical MSF errors. This is done only by using software and no further hardware has to be added to the grinding machine. Therefore this is a simple method to reduce production costs and improve surface quality in a wide range of grinding applications.

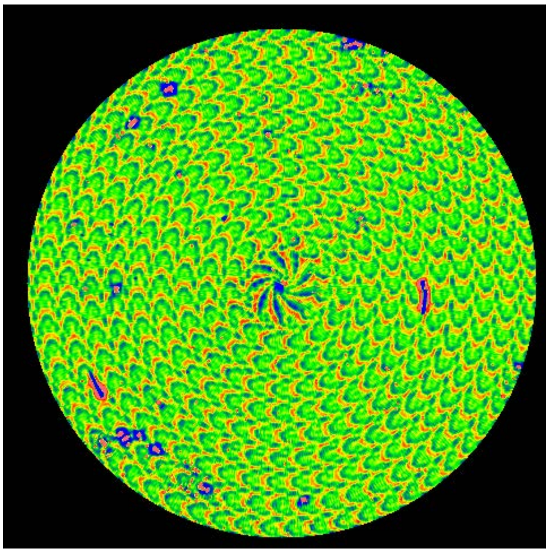

FIG. 1 False colour plot of a grinded lens (sample 1; diameter = 50 mm, Peak to valley = 5 µm). Grinding parameters which were used to manufacture sample 1: spiral path distance = 0.1 mm, rotation speed of the tool = 4333 1/min, speed on toolpath = 8000 mm/min. Nominal shape is subtracted so that the mid-spatials are clearly visible.

2 DISCUSSION

Figure 1 shows a measurement of the surface of a lens after grinding. The nominal shape is subtracted. This means that the structure which can be seen in the Figure is basically the pure error which occurred during the grinding process. The colors relate to the height of the structures (blue = low; red = high). The periodic structure of the MSF errors is clearly visible all over the surface. Remarkable is that the same grinding parameter set, on the same machine, always lead to the same structures. So it is a deterministic generation of mid-spatials which opens up the chance to build up a simulation model.

The MSF error is caused by periodic vibrations of the grinding machine. It is assumed that the strongest of these vibrations is the root cause of the mid-spatials.

On this basis a virtual model of the grinding machine was built. This model simulates exactly the kinematic of the machine and is able to calculate the position of the tool in relation to the workpiece at any time of the grinding process. At this point, it is possible to add a frequency to the tool and the

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simulation will display the new surface structure of the workpiece which resulted from the added frequency. Therefore it is now possible to determine the frequency which caused the surface structure shown in Figure 1.

The next step is to measure mechanical and physical parameters of the grinding machine [4]. It is necessary to measure the correlation between the vibration frequency of the tool and every grinding parameter which is desired to be optimized with the simulation. After these correlations were measured, the obtained data is provided to the simulation. The simulation is now able to predict the resulting surface structures on future workpieces. On this base a wide range of parameters can be simulated and it is possible to determine which set of parameters leads to the best surface quality without doing any real manufacturing tests.

3 MATERIAL AND METHODS

Figures 1, 2 and 3 show measurements of the surfaces of three lenses after grinding with different parameters. The nominal shapes are subtracted. This means that the structures which can be seen in the Figures are basically the pure errors which occurred during the grinding process. The colors relate to the height of the structures (blue = low ; red = high). All three samples were made with the same grinding machine (OptoTech ASM 100) at Deggendorf University [5, 6]. This type of grinding machine can do spiral shaped or meander shaped tool paths. All three samples have been manufactured with a spiral shaped tool path, because on a spiral shaped tool path, the MSF error emerges in periodic structures and is easier to be seen. But the principle could be transferred to any other kind of kinematic. The exact grinding parameters which were used for each sample are displayed below the figures of the samples (Figures 1, 2, 3).

The used tool was a rectangular shaped grinding wheel with a tool radius of 48.325 mm. The material of the samples is quartz glass. All samples have been manufactured several times, to make sure the same grinding parameters always result in the same structure on the surface.

The peak to valley value (PV) is the difference between the highest and the lowest point of the three measured error structures. It is always about 5 µm. The size of the PV depends on the amplitude of the frequency and the hardness of the workpiece. Therefore it can be neglected in the simulation, because it only influences the depth of the structures and not their form.

4 RESULTS

4.1 Simulation

The first attempt is to use the approach of Heinzel et al. [7] to simulate the mid-spatial surface structure seen on the grinded lens elements.

In this approach the kinematic path of a single grain cutting edge is described mathematically through the material in contour grinding. This single grain generates a cutting path over the component surface which is visualized.

The results of our simulation do not match with the generated surface patterns on the real ground surfaces in any case. Figure 4 shows a comparison between the measured surface of sample 1 and the related simulation result based on the Heinzel approach.

The second approach assumes a Gaussian shaped jitter on the tool rpms. The tool rpms varying from e.g. 4328 rpm to 4338 rpm for sample 1. Figure 5 shows four different attempts to simulate the MSF structure on the surface of sample 1 based on the jitter approach. The behavior of the single jitters is ran-

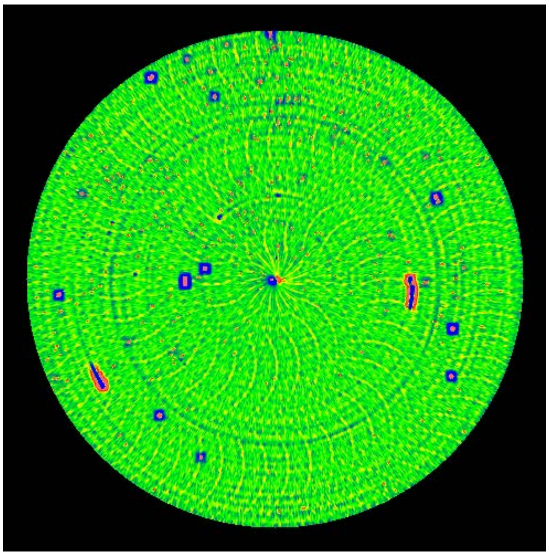

FIG. 2 False colour plot of a grinded lens (sample 2; diameter = 50 mm, Peak to valley = 5 µm). Grinding parameters which were used to manufacture sample 2: spiral path distance = 0.1 mm, rotation speed of the tool = 4555 1/min, speed on toolpath = 8000 mm/min. Nominal shape is subtracted so that the mid-spatials are clearly visible.

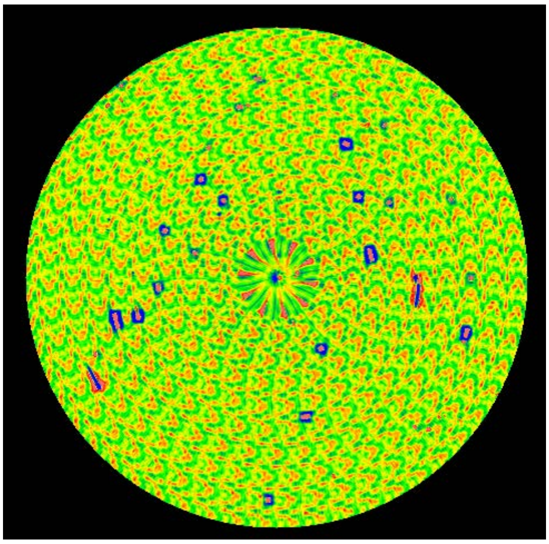

FIG. 3 False colour plot of a grinded lens (sample 3; diameter = 50 mm, Peak to valley = 5 µm). Grinding parameters which were used to manufacture sample 3: spiral path distance = 0.1 mm, rotation speed of the tool = 4800 1/min, speed on toolpath = 10000 mm/min. Nominal shape is subtracted so that the mid-spatials are clearly visible.

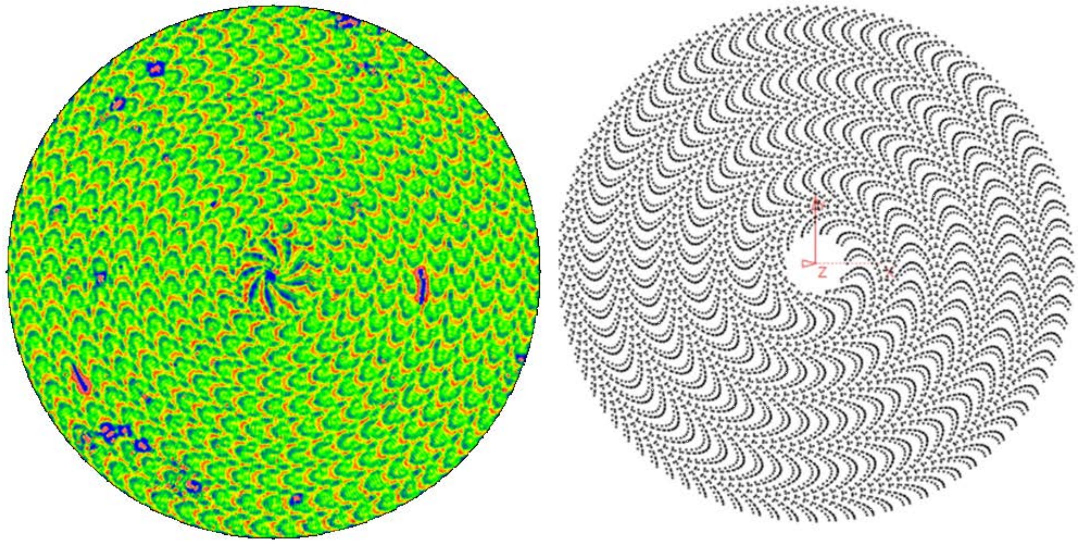

FIG. 4 Comparison between the measured surface of sample 1 (left side) and the related simulation result based on the Heinzel approach (right side).

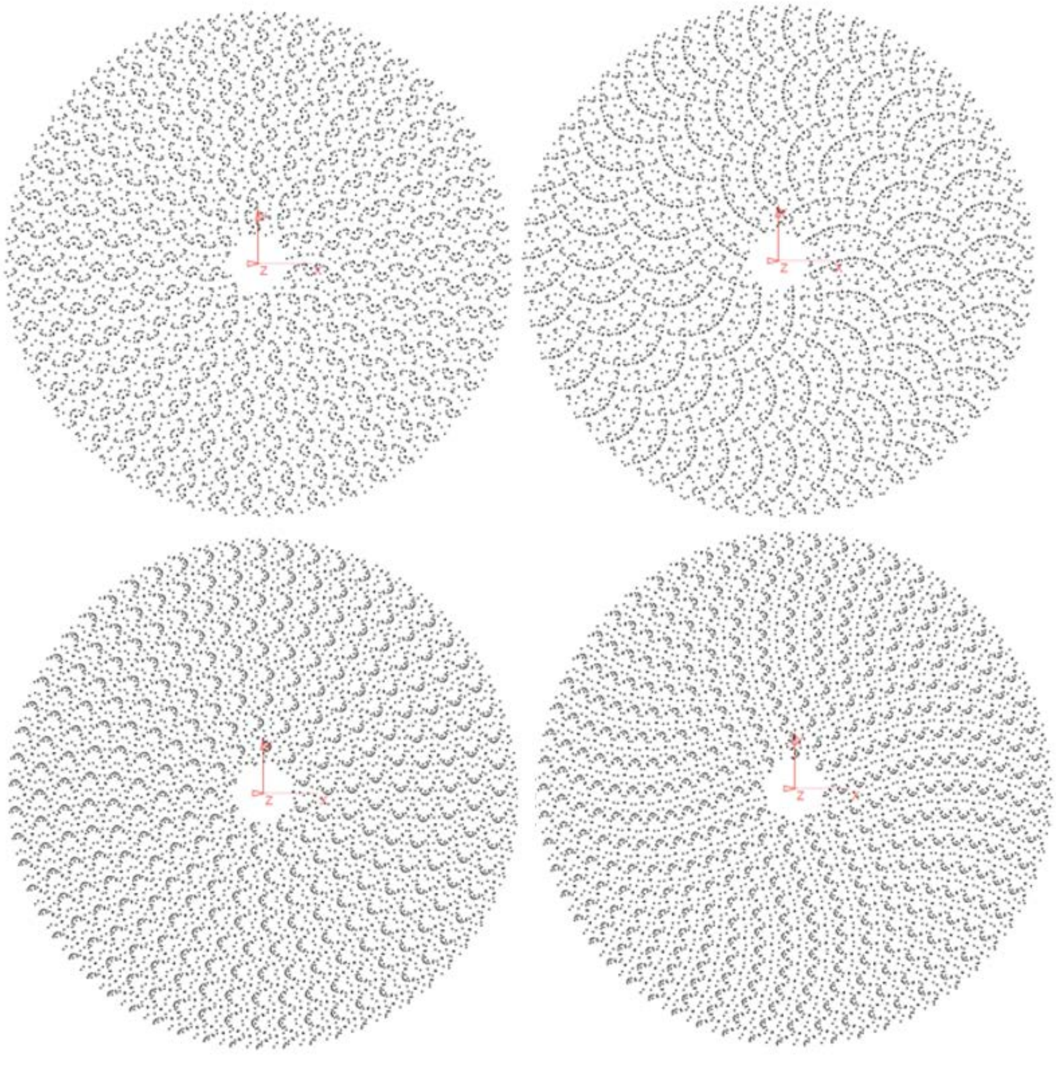

FIG. 5 Four different attempts to simulate the MSF structure on the surface of sample 1 based on the jitter approach.

dom but summed up, the whole jitter will have a Gaussian distribution. The simulated MSF structure sometimes looks very similar to the real surface (e. g. bottom left corner), but only by chance. Sometimes the simulated MSF structure is totally different to the real surface structure (other corners). This means even a small jitter of the tool rpm can cause a big difference in the resulting surface structure.

Therefore the resulting surface structure gets highly randomized by jittering the tool rpm. Due to the fact that the same

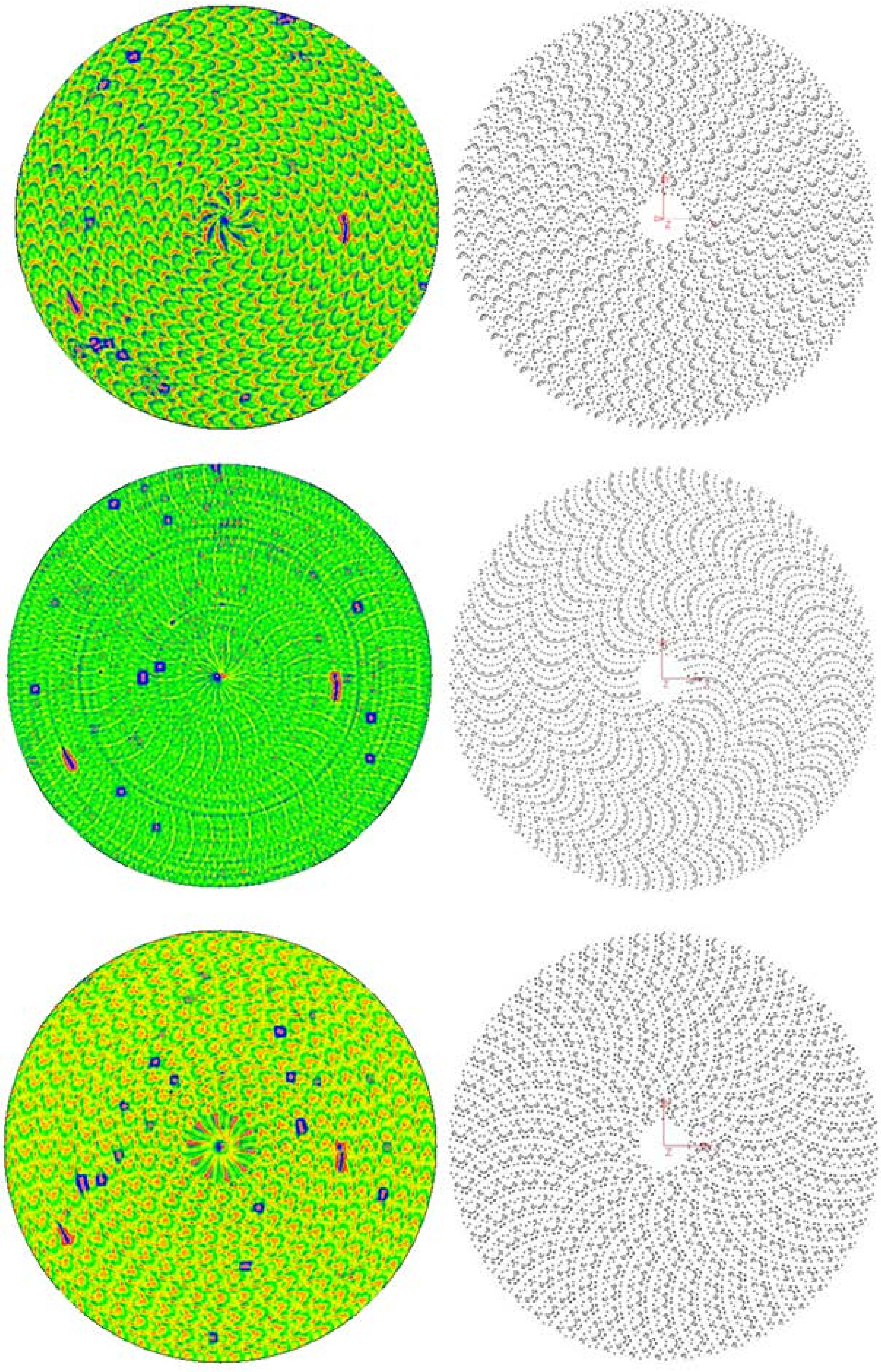

FIG. 6 Comparison between the measured surfaces of sample 1, sample 2 and sample 3 (left side) and the related simulation result based on the machine vibrations approach (right side). The vibration frequency which was determined by the simulation to cause the surface structures is 50.854 Hz for sample 1, 47.499 Hz for sample 2 and 55,092 Hz for sample 3.

grinding parameters always lead to same surface structures, there cannot be such a jitter in the grinding process. Therefore the jitter is not a successful approach.

The third and successful approach is to assume that the MSF error is caused by periodic vibrations of the grinding machine. It is assumed that the strongest of these vibrations are caused by electric frequencies in the control systems of the machine. Therefore the time period of the spatial frequencies, seen on the surface, should be close to 50 Hz.

The Figure 6 shows a comparison between the measured surface structure of each sample and the surface structure which was predicted by the simulation. The Correlations between the surface structures of the manufactured samples and their predicted surface structures are very high. Based on this third approach, the developed simulation is able to successfully predict surface structures or MSF errors which get created during the grinding process.

The different vibration frequencies which were determined by the simulation to cause each surface structure on the three samples were: 50.854 Hz for sample 1, 47.499 Hz for sample 2 and 55,092 Hz for sample 3. As expected these frequencies are close to the 50 Hz which indicates some correlation with the frequency of the power grid.

In the Figures 1, 2 and 3 you can see a change of the surface structure close to the center. To keep the speed on toolpath constant, the acceleration of the turning axis of the grinding machine has to increase while the tool gets closer to the center. At some point close to the center, the grinding machine reaches its maximum acceleration and the speed on the toolpath can no longer be kept constant. Because of this reason the structures have only been simulated to this point and the centers were left empty in the simulation.

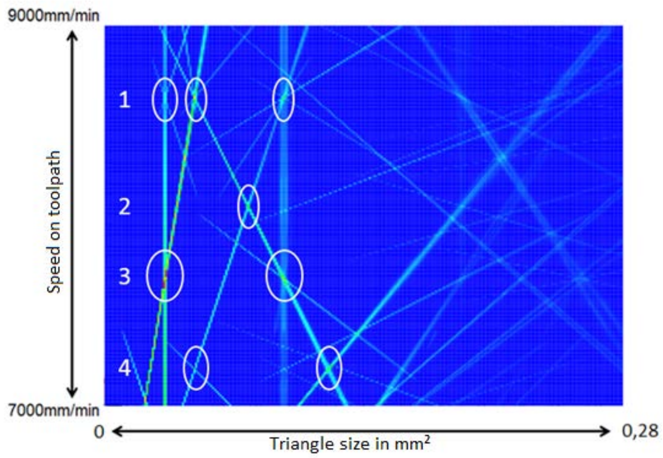

FIG. 7 Histogram for the evaluation of a parameter range (the red marked cut points reveal parameter sets of interest).

4.2 Optimization

As previously mentioned it is also possible to optimize a grinding parameter. For this purpose it is necessary to simulate a range of this parameter. E. g. to find the ideal

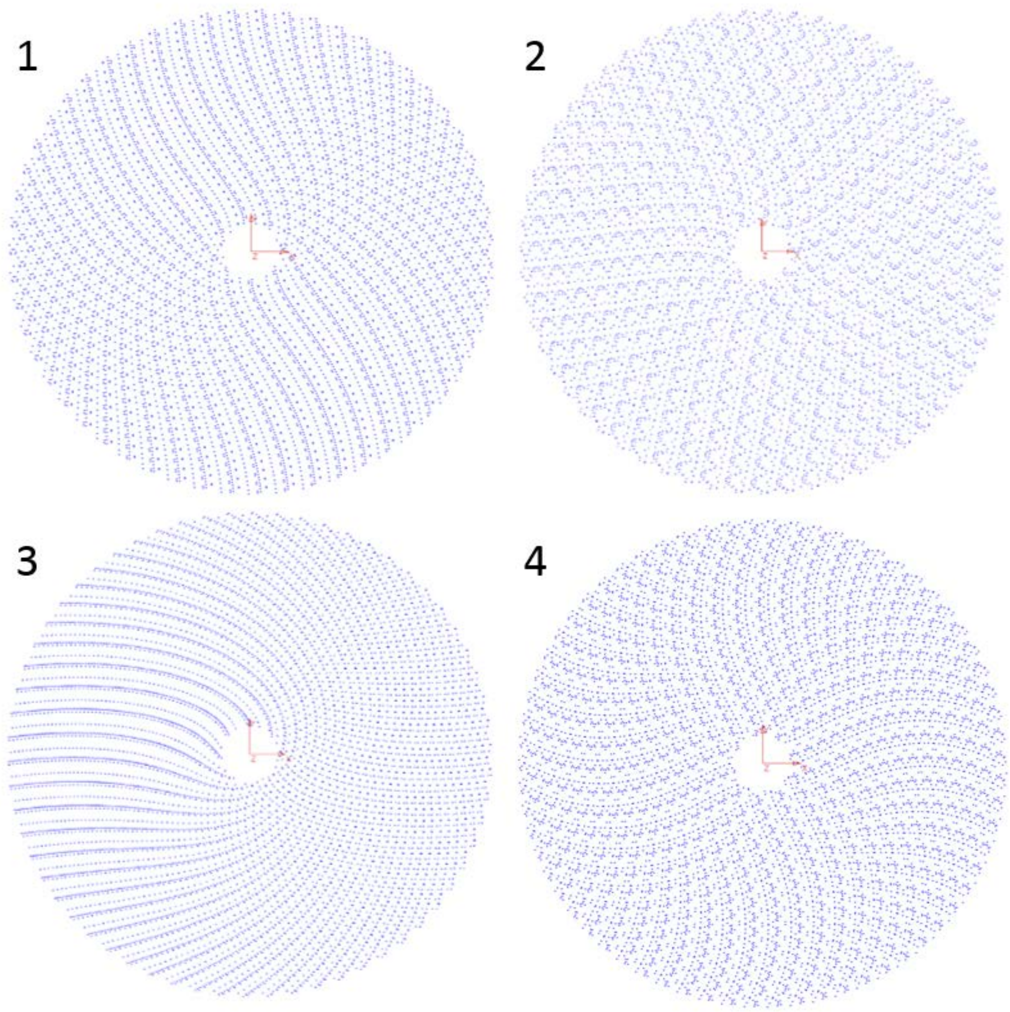

FIG. 8 Very homogenous and less problematic surface structures which would result from the marked parameter sets in Figure 7.

Speed on tool path, all tool path speeds between 7000 and 9000 mm/min are simulated. The resulting prediction for each speed is evaluated by a Delauney triangulation based Algorithm. The predicted structures get connected to a network of triangles. The area size of these triangles is displayed in a histogram for every different speed (XY-Plane). After that, all the different histograms get placed side by side and analyzed from above (XZ-Plane). Figure 7 shows such a set of histograms. The pale lines show the progression of the histogram peaks across the simulated parameter range. Whenever these lines cut each other, this indicates a special parameter set which leads to a very consistent surface structure. This cutting points are marked in Figure 7 and Figure 8 shows the special structures which would result from these parameter sets.

5 CONCLUSIONS

In this paper the kinematics of the grinding process were analyzed in order to model the grinding process and resulting MSF errors which can be observed. The model was used to simulate the generation of MSF surface patterns. It was shown that the results of the simulation matches with the real MSF surface patterns. The key element of the simulation is that a fixed vibration frequency close to the 50 Hz (the frequency of the power grid) explains the MSF error structure

Based on this 50 Hz frequency it is possible to predict the resulting surface structure of a grinding process using a simulation model. Therefore the goal to create a simple and cost efficient approach, with the aim to reduce and control MSF errors was achieved.

The single grinding parameters can be optimized until one or more parameter sets are determined which result in a minimum of critical MSF-errors. These parameter sets can be found by searching for cutting points of the histogram peaks. It would be also possible to define a structure which is uncritical for the application or easy to remove with existing subaperture polishing processes. Then the optimization could search the parameter sets which lead to a structure which is as similar as possible to the structure which was defined. This could be interesting for optical design applications.

6 ACKNOWLEDGEMENTS

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