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Enhancing geometric accuracy in 2PP through voxel geometry-based CAD design adjustments

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Abstract

The two-photon lithography is a high-precision additive manufacturing technology that enables the fabrication of complex three-dimensional structures with resolutions below the diffraction limits of commercial laser fabrication systems. To exploit the advantages of this technology and to ensure a high functionality of the final product, the manufacturing-related deviations between design and product have to be investigated. Since the deviations are depending on different factors like the shrinkage, the voxel geometry, and the writing-process, a suitable dynamic compensation is needed. Various aspects of the process influence the formation of the voxel. Some of these factors are the optical system with the wavelength and the objective, as well as the material properties. These factors are directly influencing the form fidelity and thus, determining the structure.

The research work presented here focuses on the investigation of manufacturing-related deviations and the development of compensation methods. Next to the manually compensation based on linear regression, a programme was developed and implemented in python, which calculates a compensated STL-design based on the voxel geometry. In the first step the compensation was tested in a setup where the voxel geometry is known. An empirical study with a target design is performed for the validation of the program. Since the voxel geometry depends on various parameters and is not always known to the machine operator, the program has to be adjusted to real operation environments. Usually, the machine operator uses process parameters in a specifically suitable process window. The goal is to decrease the number of iteration cycles for achieving a high form fidelity and therefore, to provide faster prototyping.

Two-photon lithography, compensation, hybrid polymers, laser direct writing

1. Introduction

The two-photon lithography (TPL) is a direct laser writing technology that stands out from other manufacturing processes for its ability to fabricate complex 3D geometries with extreme high resolutions (>0.2 µm) and without the need of supporting structures. The process is based on the two-photon polymerisation, in which two photons from a high energy laser source have to be absorbed almost simultaneously by one initiator molecule to induce a chemical reaction [1]. The photon density in the focal spot of the laser is high enough to trigger the chain reaction for the polymerisation process. Since the focal spot has a defined spatial energy distribution, the resulting polymerized volume (voxel) is elliptically shaped. The size of the voxel depends on various factors, like the laser wavelength, the laser power and the material properties. The unique characteristics of the polymerisation process enables the fabrication of features below the resolution limit of the optical setup, in the range of a few hundred nanometre [2].

The high resolution and ability to produce complex freeform structures pushes the two-photon lithography at the focus of research for the development of prototypes in the fields of medicine, biotechnology, microfluidics and photonics [3,4]. These fields have high requirements on the functionality and form fidelity of the end product [5]. To this day just a limited amount of research exists that focus on geometry accuracy of end products. Fabricated structures experience surface tensions, over polymerisation and other interactions that impact the geometry [5]. This means that manufacturing-related deviations have to be investigated and compensated to ensure high functionality and accuracy. Since the deviations depend on various process parameter and the used materials, many iterations are necessary to compensate the structures. One of the main causes for deviations between design and product is the voxel size. Since this value is depending on different factors, a general software solution for the compensation is not available for some TPL-workstations. Therefore, an investigation of the influence of different parameter settings for a specific test structure is performed in the study to determine the deviations. The results will be used to generate a compensation program to reduce the iteration cycles for obtaining reasonable form fidelity.

2. Methods

Manufacturing related deviations are mainly caused by the voxel geometry. These parameters are highly responsible for the intensity distribution that induces the polymerisation process. Other factors are the material properties and the material shrinkage that have an impact on the form deviations. The deviations can affect the functionality of the end structure, especially for optical components. A high degree of dimensional accuracy is necessary to ensure the designed characteristics.

Typically, TPL systems are using an STL or CAD design to derive the laser path for the fabrication. Since the voxel geometry varies depending on the parameter setting, the voxel centre is used to follow the laser path (see. Fig. 1). This results in deviations between the design and the end product.

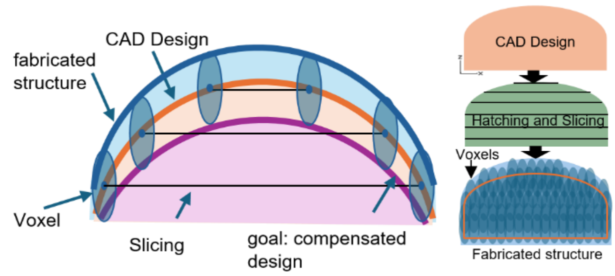

Figure 1. Depiction of the design (orange,) the end product (blue), and the fabrication of the structure, with an optimal compensated design (purple)

Therefore, the goal of this work is to reduce the deviations below 5 % to ensure a high functionality and accuracy. A test series will be performed and a compensation programme developed to reduce the deviations based on the voxel geometry. The following equipment and components were used to perform the tests and measurements.

2.1. Equipment and Material

<u>Two-photon lithography:</u> The tests were performed with a FemtoLAB from the company Workshop of Photonics (WOP, Lithuania). The laser provides wavelength of 1028 nm, 515 nm and 343 nm and a maximum laser frequency of 601.8 kHz. In this study the wavelength 515 nm with a pulse duration of 244 fs was used. The laser was focused with a 63x objective (NA 1.46, Zeiss) and an immersion oil. The following parameters were used in the fabrication of the test structures.

Table 1 Process parameter-set for the fabrication of the test structures

P [mW]	v [mm/s]	Dz [µm]	HW [µm]	PD [p/mm]
85.5	15	0.1	0.1	20000

<u>Hybrid polymer:</u> As material for the test structures, the hybrid polymer SZ2080 (FORTH, Greece) was selected. The polymer was prebaked on a glass slide for 8 hours at max. 90° (40°C/1h, 70°C/1h, 90°C/6h). After the fabrication the sample was immersed in a mixture of 1/3 isopropanol and 2/3 isobutanol methyl ketone for 20 minutes. The sample was rinsed with isopropanol and air dried before further investigations.

<u>Laser scanning microscope:</u> The measurements were performed with the VK-X3000 laser scanning microscope from Keyence (Japan). For the profile measurements of the test structures a 100x objective with an NA of 0.95 was used. The VK-X3000 is suitable to perform profile measurements for transparent structures, and the resolution of the system is below 50 nm in all axis. The data was analysed with the software *multifile analyzer* provided by Keyence.

2.2. Test structures

The test structure was chosen based on the complexity of the compensation but simple enough to estimate the required compensation by iteratively adjusting the structure. In addition, similar structures are international benchmarking standards to assess the capabilities of TPL systems [4].

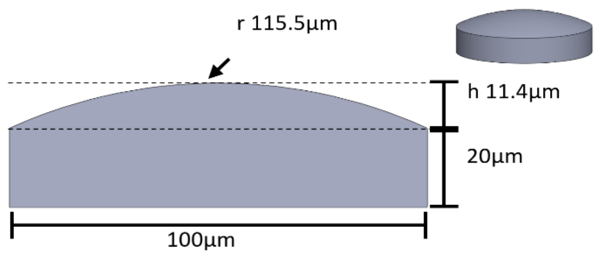

Figure 2. CAD Design of the test structure (H11)

An optical setup was designed that consists of a base with a diameter of 100 µm and a hight of 20 µm, and a lens with a radius of 115.5 µm and an apex height of 11.4 µm (see Fig. 2). The depicted structure with an apex height of 11.4 µm is further referred to as H11.

2.3. Compensation program

The iteratively design adjustment to compensate fabrication related deviations is time consuming and resourceful. Therefore, a program was developed to compensate the deviations based on the voxel geometry and calculate a new design, that should match the desired form after the fabrication. The adjustment is performed using a geometry-based compensation model, which performs a normal-based shift of the mesh surface of the input STL based on the voxel geometry. The anisotropic offset is calculated along the surface normal, where the offset is locally weighted depending on the normal orientation. Due to the voxel geometry, the shift must be calculated using an ellipsoidal offset. To reduce local artifacts caused by the compensation and to increase the surface smoothness of the model, a selective Laplacian smoothing can be applied. After adjusting the model an STL file is created based on the modified structure, which can directly be used for manufacturing. The figure 3 depicts the desired compensation along the surface normal.

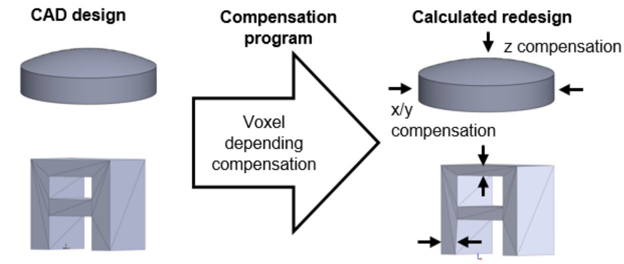

Figure 3. schematic representation of the CAD (left) and the compensated redesign (right)

3. Experiments

The first tests were performed to investigate the deviations induced with the selected process parameters and to manually compensate the design based on the findings. The test structures were printed at least three times and the radius measured and averaged with *multifile analyzer*. The predefined function *Arc R* was used to analyse the radius at 10 different orientations along the surface. Next to the original design H11, five derivations are printed to calculate the compensated design for a high dimensional accuracy. The structures and the results can be seen in table 2. A compensated structure with a radius of 138.31 µm and an apex height of 9.34 µm can be determined from the measured values by using linear regression.

Table 2 Measured radius for different test structures

Name	Apex height	Designed r	Measured r
H11	11.4 µm	115.25 µm	98.23 µm
H10	10.0 µm	130.00 µm	105.30 µm
H9	9.0 µm	143.38 µm	124.64 µm
H8	8.0 µm	160.35 µm	130.81 µm
H7	7.0 µm	182.07 µm	143.04 µm
H6	6.0 µm	211.33 µm	174.38 µm

The adjustments of the compensation program are based on previous investigations of the resulting voxel dimensions depending on various process parameters. Further details on the investigation of the voxel geometry, the test series and the result can be viewed in [6]. The dimensions of the voxel corresponding to the process parameter was used to estimate positional deviations along x-, y- and z-axes, with the maximum z axis correction limited to z/2 (half of the voxel hight). Other configurable parameters of the program are the compensation factor, the number of Laplacian smoothing iterations, and the smoothing weight. Since the deviation is calculated along the surface normal, the compensation is maximal in the z-direction, particularly in areas with high surface curvature. In regions with low curvature the deviation in y and y is minimal. As a result, the apex of the lens, where the normal are almost entirely in z, was disproportional high corrected. This leads to a localized overcompensation that shows up in the compensated model as a surface depression at the apex (see Fig. 4). This compensation artifact can be reduced by optimizing the smoothing parameters and compensation thresholds in the programme.

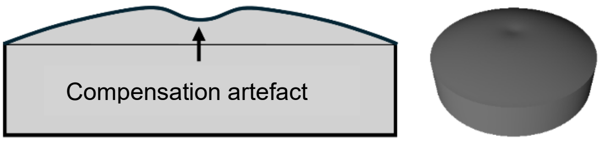

Figure 4. Exaggerated representation of the artefact induced by the surface normal compensation

4. Results

The test series has to be performed multiple times to generate robust results and to exclude random fabrication errors. Although the manually approach is inefficient and only valid for this structure and process parameters, the deviation between the desired design and the fabricated structure could be reduced from 14% down to 2.5%. One problem with this approach is that it is only applicable for simple surface geometries, but is difficult to implement for undercuts or more complex structures.

On the other hand, the compensation program is a universally applicable approach and is valid regardless of the design. Different compensation parameters were tested to generate STL files. The maximum offset, the repetition of the Laplacian smoothing and the weighting factor were varied to optimize the predicted offset. The program parameter can be seen in table 3.

Table 3 varied program parameter for optimizing the compensation

Name	Max. offset	Laplace repitition	Weighting factor	Deviation %
L1	z/2.5	20	0.5	7.9
L2	z/2.0	20	1	3.7
L3	z/1.5	40	1.5	2.8

The test indicated that L3 has the highest correlation between the measured radius and the designed radius from the structure H11. Another test structure will be used to confirm the robustness of the program. The second test is intended to validates that the compensation program is suitable for improving the dimensional accuracy for different structural designs.

Since the fabrication deviations between the same structure with unchanged process parameter can have a difference in the radius of up to 3 % (apex height: <2 %/0.2 µm) for structures on the same sample and 5 % (apex height: <5%/0.6 µm) between different sample. The achievable compensation with both approaches is sufficient to increase the reachable dimensional accuracy.

The compensation program can be further improved by adding additional test series and measurements by adjusting the program parameters to achieve the smallest possible deviation between reality and desired structure. Additionally, the compensation artefact can be reduced using other smoothening operations. Furthermore, other factors that influence the shape, such as hatching and slicing, or shrinkage effects, can be included in the model. The compensation program has to be validated for different geometries and parameters to ensure a high robustness and correlation.

5. Summary

The two-photon lithography enables the 3D manufacturing of structures in the sub-millimetre region with high resolution down to 200 nm. The ability to produce complex freeform components pushes the process at the centre of research for prototyping in various fields. In most cases a high form fidelity is required to ensure the functionality of the prototypes. Therefore, the analysis of manufacturing-related derivations is necessary to compensate the design and to increase the geometrical accuracy.

This work is dedicated to the investigation of manufacturing-related deviations and the development of compensation methods to increase the geometrical accuracy between design and end product.

A simple test structure was designed to test two approaches for the compensation. First the test structure was manually adapted, printed with the same parameter sets and measured. The results were used to perform a linear regression to determine the optimal compensation to fabricate a structure with the desired radius. In the second test series a compensation programme was developed that adapts the test structure based on the voxel geometry, resulting from the process parameters. Different combinations from the adjustable parameters of the programme were tested and the deviations measured. At the end a suitable programme parameter set was selected for compensation. The manually adapted compensation has the lowest deviation from the desired values. In contrast, the compensation programme has slightly higher deviations but reasonable improvements in less iterations. Depending on the application both approaches are applicable, where the compensation programme is more versatile.

This study proves that the manufacturing-related deviations can be successfully reduced to values below 5 %. Different approaches can be used to compensate these manufacturing-related deviations. The compensation programme is a universally applicable approach to compensate structure when the voxel geometry is known. Further investigations and improvements of the compensation programme are required to confirm its applicability to more complex structures.

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