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Laser Lapping of Piezoelectric Ceramics using Ultrashort Pulse Laser and Closed Loop Control Algorithm

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Abstract

A key part of a deformable mirror is a piezoelectric ceramic, which provides the deformation of the surface by a supply voltage. The mechanical surface flattening of these ceramics leads to unpredictable new deformation of the ceramic due to the mechanical stress during the lapping process. Ultrashort pulse lasers can be used to ablate a small amount of material volume with low thermal influence and low mechanical stress to the processed material. In this study, we demonstrate the combination of inline topographic measurement and ultrashort pulse laser ablation for local material removal of a piezoelectric ceramic. A differential model of the surface was built, and the surface deformation after the laser treatment was measured. The material properties regarding the ablation efficiency and roughness after laser treatment are investigated. The flatness and the roughness of the surface after the laser process are compared to the mechanical process.

Keywords: Laser Micro Processing; Laser System Technology and Process Control; Deformable Mirror; Laser Ablation

1. Introduction

Piezoelectric ceramics are reacting to an external supply voltage by changing its thickness (Verpoort and Wittrock 2010). The deformation range depends on the thickness of the ceramic and the external voltage. The typical change in thickness is in the range of a few micrometers. This fine-tuning allows high precision positioning, e.g. of mirror mounts. They can also be used for deformable mirrors. In this case, one of the electrodes is separated into several segments and therefore, allows precise manipulation of the ceramic

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deformation (Smarra and Dickmann 2015). For the construction of a deformable mirror, a low initial deformation of the raw piezoelectric ceramic is necessary. However, most raw ceramics have an unacceptable high initial deformation. A typical processing step to reduce the initial deformation is the mechanical lapping of the surfaces. After the mechanical lapping process, the ceramic substrates show better quality than before. Though, even a two-sided mechanical lapping shows deformations in the range of a few tens of micrometers.

The further reduction of the deformation may be achieved with selective laser ablation using a picosecond laser. Ultra-short laser pulses offer the defined material ablation with low thermal influence to the surrounded material (Nolte et al. 1997). Especially when considering a piezoelectric ceramic, it is essential to reduce the thermal influence to the material: On the one hand, the material might be damaged due to high thermal induced mechanical stress. On the other hand, a depolarization occurs, if the material is heated above a material specific Curie temperature.

This paper demonstrates a full process sequence

- beginning with the initial surface deformation and the influence of mechanical lapping,
- a parameter study regarding the ablation efficiency of the analyzed piezoelectric ceramic,
- building a differential model for selective laser ablation
- comparing the deformation of the laser lapped surface to the mechanical lapped surface

2. Experimental Setup

For this study, an industrial-standard picosecond laser (Trumpf TruMicro 5050) with an average power of P = 50 W, a pulse duration of τ = 8 ps and a wavelength of λ = 1030 nm was used. The laser beam was deflected and focused onto the surface by a Scanlab Hurryscan II – 14 and an f-θ-lens with a focal length of f = 100 mm. The surface of the piezoelectric ceramic was measured using a chromatic sensor (Precitec CHRocodile S) with a measuring range of 0.66 mm. The accuracy of the sensor is 0.2 µm. Linear stages are used to move the ceramic to the laser and the sensor. This is necessary to achieve high accuracy when repositioning the sample. More information on this setup were demonstrated in (Smarra et al. 2015).

The sample material for this study is a 500 µm thick PIC 151 and a 700 µm thick PIC 181. The material characteristics are shown in table 1:

Table 1. Material characteristics of the investigated piezoelectric ceramics

Material	Density [g/cm³]	Curie temperature [°C]	Indication
PIC 151	7.8	250	Soft
PIC 181	7.8	330	Hard

3. Results

3.1. Influences to the surface deformation of a piezoelectric ceramic by mechanical lapping

A 200 µm thick PIC sample was analyzed to investigate the influence of mechanical lapping on surface deformation. During the lapping process the silver coating (approximately 15 µm thick) on the lapped is removed. The results are shown in Fig. 1: a) shows a raw piezoelectric ceramic with an astigmatic deformation and a peak-to-valley deformation of approximately 300 µm. The deformation is larger than the thickness of the piezoelectric ceramic. A one-side lapped ceramic (b) results in a concave deformation of the surface. The peak-to-valley value reaches 380 µm and is larger than the unlapped ceramic. When both sides are lapped (c), the peak-to-valley deformation of the concave is reduced to approximately 60 µm. The same z limits were chosen, so the deformation of sample c) is nearly not recognizable in this figure. These results are for demonstration and vary within each charge. The measurements in Fig. 1 were not perfomend on the same ceramic., They demonstrate the general influence of the lapping process to the surface of the ceramic, but not the scaling of the deformation.

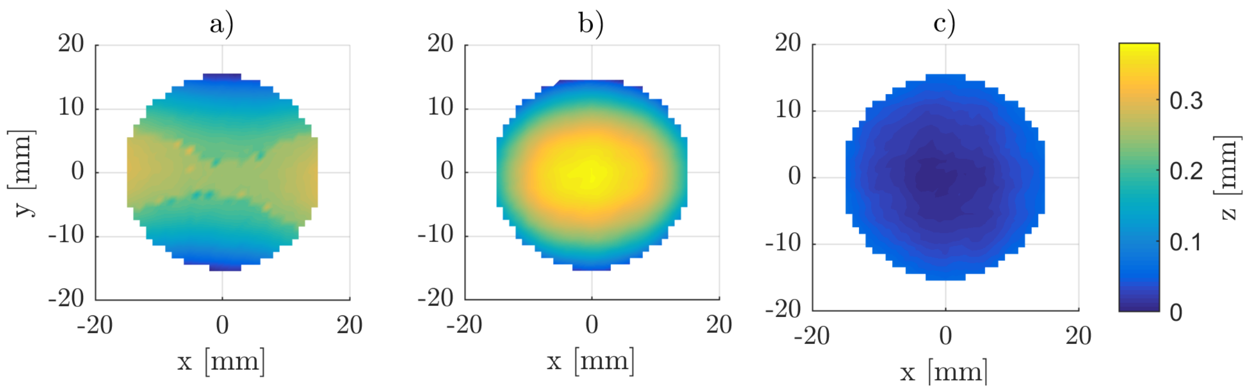

Fig. 1. (a) unlapped piezoelectric ceramic with an astigmatic deformation with a peak-to-valley of 300 µm; (b) one side is lapped with primary concave p-v deformation of 380 µm; (c) two sides are lapped piezoelectric ceramic with a primary concave p-v deformation of 60 µm

3.2. Laser processing parameters

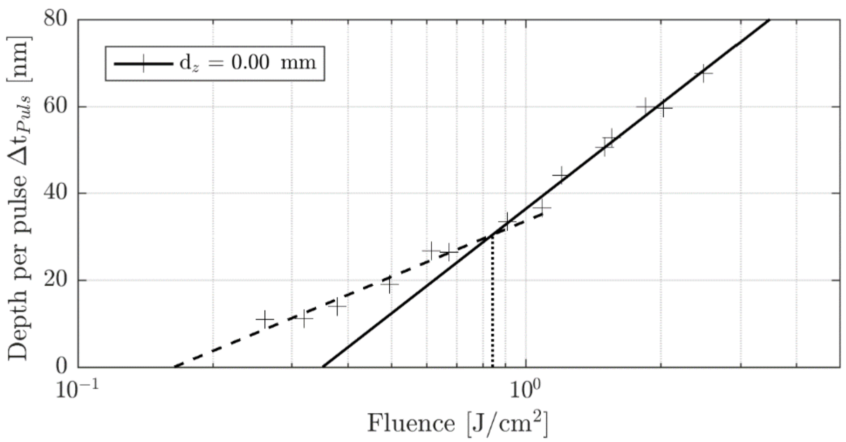

Fig. 2. Threshold fluence for the investigated piezoelectric ceramic. For this study, a fluence near the ablation threshold was chosen, to keep the ablation depth per run at a low level. The ablation threshold was determined to be $F_{th,abl} \approx 0.16\, J/cm^2$ while the strong ablation regime begins at $F_{th,strong} \approx 0.84\, J/cm^2$.

Appropriate laser parameters are necessary for selective material ablation of the piezoelectric ceramic. For this purpose, the threshold fluence needs to be investigated: Small cavities with defined outer dimension were structured, and the depth of the cavity was measured using the chromatic sensor. The depth achieved per pulse and scan run depending on the the laser fluence is shown in Fig. 2. The two ablation regimes (gentle and strong) can be seen due to the difference in the slope of the linear fitted lines. For this investigation, a fluence in the gentle ablation regime was chosen in order to keep the ablated material per run at a low level. The determined ablation parameters are shown in table 2. The determined values are measured for a pitch of 5 µm between two laser pulses. A variation in the pitch between two consecutive laser pulses leads to a change in the threshold fluence, due to the incubation factor.

Table 2. Material characteristics for the ablation of PIC151

Parameter	Formula	Unit	Value
Ablation threshold gentle regime	$F_{th,Abl}$	J/cm^2	0.16
Penetration depth gentle regime	δ_1	nm	18
Ablation threshold strong regime	$F_{th,strong}$	J/cm^2	0.84
Penetration depth strong regime	δ_2	nm	34

With the knowledge of the ablated volume, the theoretical processing time and the average power on the surface, the ablation efficiency can be determined, see Fig. 3. The theoretical processing time is used to eliminate process dependent delays like acceleration or deceleration of the scanning mirrors. The highest ablation efficiency can be achieved with a fluence of about 0.6 J/cm². After this maximum, the ablation efficiency drops. High fluences in the strong ablation regime also lead to an increase in surface roughness (J. Schille, L. Schneider, L. Hartwig, U. Loeschner). In this setup, fluences below 0.25 J/cm² cannot be achieved, if the waist of the laser is positioned onto the surface. This leads to a mismatch in threshold fluences between the fits in Fig. 2 and Fig. 3.

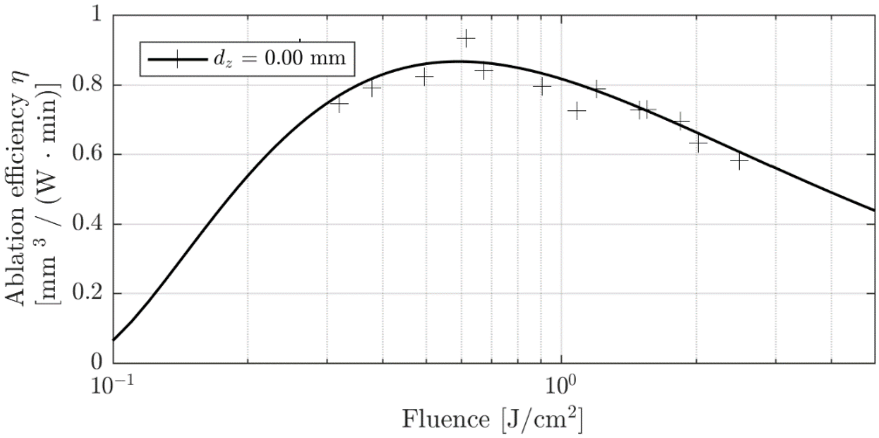

Fig. 3. Ablation efficiency for the investigated piezoelectric ceramic. The highest ablation takes place at about 0.6 J/cm². At higher fluences the ablation efficiency drops and more thermal influence to the ablated region.

3.3. Difference model of the surface and selective laser process

Due to the high deformation of the thin piezoelectric ceramics, see fig. 1, the surface flattening by selective laser ablation was tested on thick samples (500 µm, PIC 151). Therefore, the surface deformation was measured, and a differential model was generated for selective material removal: the more material needs to be removed in a specific section, the more scan runs are used in this area, see example in Fig. 4.

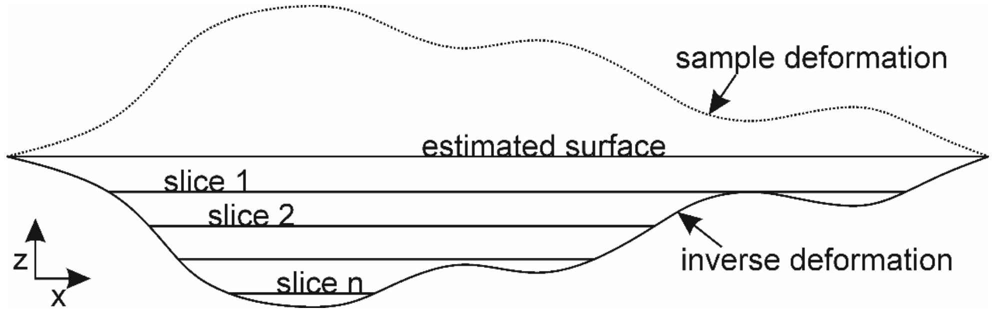

Fig. 4. Example of the slicing process: the higher the deformation of the sample, the more material needs to be removed to achieve the desired surface. For this purpose, the inverse surface is built and separated into several slices with the same thickness.

The initial deformation of the untreated ceramic was measured using the chromatic sensor. The overall deformation was determined to be about 40 µm. The laser parameters chosen for the ablation, result in a layer thickness of 5-6 µm. After two runs of laser ablation, the total deformation was reduced to less than 20 µm. However, an increasing number of runs does not lead to a further reduction of the overall deformation. The reasons need to be investigated in the future. One reason my be internal stress of the material or the result of the thick slicing steps of 5-6 µm. A further reduction of laser energy leads to a reduction of the ablated depth per run and may be needed to increase the accuracy of this process.

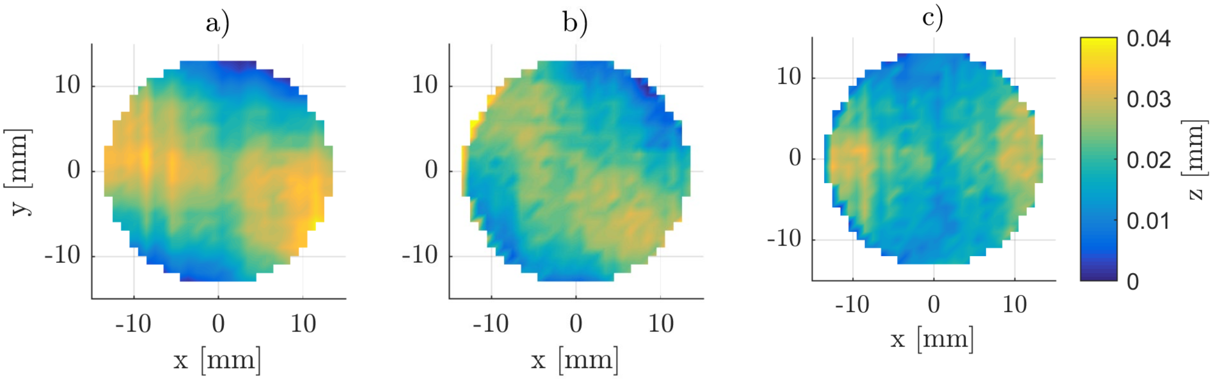

Fig. 5. (a) untreated surface with an astigmatic p-v deformation of 40 µm (b) surface after two runs of selective laser ablation with a total deformation of less than 20 µm (c) absolute value of the removed material: most of the ablated material was removed on the outside.

4. Conclusion and Outlook

In this study, it is shown that a reduction of the total deformation of a piezoelectric ceramic can be achieved by selective laser ablation. A combination of topographic analysis and laser treatment within the same machine is used for an automatic process. At first, the influence of mechanical lapping on the surface deformation of thin piezoelectric surfaces is shown, to demonstrate the necessity for further laser treatment. Subsequent, the ablation behavior of the piecoelectric ceramic was investigated to determine the ablation threshold via the ablation per pulse and the ablation efficiency, see Fig. 2 and 3. This investigation is necessary to find a parameter setting which leads to a low thermal influence to the piezoelectric ceramic, which is fundamental to keep the material below the Curie temperature. Finally, the selective laser ablation process is demonstrated on an astigmatic deformed surface of a piezoelectric ceramic after removing the silver coating: The deformation is measured with the chromatic sensor, the inverse surface is built and sliced into several layers with an overall thickness of 5-6 µm. The demonstrated process reduces the initial surface deformation from 40 µm to less than 20 µm within two runs.

However, a further reduction could not be achieved and needs to be investigated in the future. A recursive process will also be tested: After a specific number of layers, the surface deformation will be measured, and the following layers will be adapted to this deviation.

Acknowledgments

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