OPEN LOOP FAST TOOL SERVO WITH NANOMETER ACCURACY FOR DIAMOND MACHINING OF DIFFRACTIVE STRUCTURES

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INTRODUCTION
Many security applications use diffractive optical elements (DOE) for the proof of the genuineness of products e.g. software licenses or Euro-banknotes. They are mostly made in long, time-consuming and expensive process chains. Since it is a mass product the individual DOE or hologram is inexpensive. However, there are almost no technologies known for making cost efficient individual DOEs for highly sophisticated products. To fill this gap, a diamond turning process was developed for machining individual arbitrary diffractive patterns. The key component is the developed nano fast tool servo (nFTS). It enables the fabrication of DOEs with any step height between 0 and half of the wavelength that can not easily achieved by common structuring methods like gray-scale lithography or laser ablating technologies. [1]

The application of fast tool servo systems is a common way to enable the generation of freeform surfaces and non rotational structures using a turning process [2,3]. It is possible to manufacture microstructures with optical surface finish. However, the commonly achievable structure density and accuracy is not sufficient for the generation of diffractive optical elements with arbitrary pattern. The main reasons are limitations regarding the system bandwidth and positioning accuracy [4,5]. In the following a new fast tool servo technology is presented, that will enable the generation of individual DOEs for security applications.

EXPERIMENTAL SETUP & MACHINING PROCESS
The diamond machining process for machining energy efficient DOEs using a fast tool servo requires a well tuned combination of all participating components as well as the process itself. The major components of this system are the type of DOE structure, the nFTS and the positioning system, the shape of the diamond tools cutting edge, the workpiece material and the machining process. All components have requirements to others. The following description of the major components will give an overview of the setup as well as the most important requirements.

DOE Design
The data density of a diffractive optical element (DOE) depends mainly on the dimension of structure elements and the number of machinable height levels. The dimension has to be small for high data density. By individual modification of the height levels it is possible to modify the phase of light to make the step from a binary to a full modulated DOE with increased functionality. It was found that a blaze structure will fulfill these requirements taking the system components discussed below into account. In Figure 1 the topography of the blazed structure is depicted.

nFTS Setup
The key component of the developed nano fast tool actuator (nFTS) is a custom piezoelectric actuator. This ceramic has high linearity, nearly zero hysteresis and therefore negligible heat dissipation.

The nFTS is designed for the generation of discontinuous DOEs with a diameter up to 20 mm on flats (spheres and aspheres are also conceivable). The current nFTS has a bandwidth
of approx. 5 kHz with a stroke of up to 500 nm. Systematic deviations can be determined pre-process and superimposed to the nFTS control signal for calibration reasons. Therefore, it can be used in an open loop control mode while maintaining a nanometer positioning accuracy. This is the most important characteristic and the biggest advantage of this system.

Figure 2 shows the setup of the nFTS. The dimension is 40x40 mm², therefore, this system can easily integrated in ultra-precision machine tools.

**Figure 2. nFTS setup.**

### Workpiece Material & Cutting Process

Surface defects that remain on the DOE after the machining process like burr, roughness and effects of the grain structure will affect the efficiency of the DOE to be machined. Therefore, electroless nickel, nano-crystalline aluminum, OFHC-copper and several nickel silver alloys are investigated in cutting experiments for determining an appropriate workpiece material.

A straight edge mono-crystalline diamond tool with tool nose angle of 84°, a clearance angle of 6°, a rake angle of 0° and an additional minor cutting edge was used. Due to the limited bandwidth of the nFTS and the required data density of up to 3000 height levels (data) per revolution, the spindle speed has to be reduced down to 50 ... 150 rpm (v_c ≤ 3.1 ... 9.3 m/min).

Figure 3 shows the AFM images of four machined structures. Nano-crystalline aluminum suffers from low inter-crystalline bonding strength and shows a disrupted topography and high roughness values. Electroless nickel and OFHC-copper achieves low surface roughness but suffers from high tool wear and plastic deformation of the structure respectively. The nickel silver alloy (49% Cu, 39% Zn, 7% Ni, 3% Pb, 2% Mn) shows low surface roughness at low tool wear. Interestingly, the crystalline structure of the material does not effect the surface topography.

**Figure 3. AFM images of continues blaze structures for testing the material properties (20x20 mm²).**

Figure 4 shows the nFTS setup integrated in an ultra-precision machine tool. It was installed upside down for better chip removal and some aspects of the machine tool structure. The data flow to the nFTS is synchronized with the rotational angle of the workpiece by triggering the data flow with the rotational glass scale signal of the spindle-axis (C-axis). Figure 5 gives an overview of the signal flow.

**Figure 4. nFTS setup in an ultra-precision machine tool.**

**Figure 5. Signal flow.**

**Electroless nickel**

Sa = 4.6 nm

**Nano-crystalline aluminum**

Sa = 17.0 nm

**Nickel silver**

Sa = 3.1 nm

**OFHC-copper**

Sa = 5.4 nm
RESULTS
Using the system several diffractive structures have been machined and the quality of the machining process and the system design was tested. Moreover, the optical properties of the machined DOEs were evaluated by analyzing holographic images reproduced in a propagation plane.

For assessing the positioning accuracy several systems tests have been performed. Figure 6 shows an AFM image of the center of a sample with two step heights. The height difference between the rear and the front part of the structure is 400 nm. The concentric rings correspond to the structure width \( b \) (= tool feed, cf. Figure 1). The result of this experiment was that no deviation of the angular position of the height step could be measured. This demonstrates the accuracy of triggering the signal generator (cf. Figure 5) by using the angle encoder signal.

Figure 6. AFM image of a structure for testing the quality of the data trigger for the signal generator.

For determining the deviation in step height in the described open loop system a sample with 10 height levels in 50 nm steps and 10 reference levels was machined (cf. Figure 7 - top). For this experiment a radius diamond tool with a tool nose radius of 50 µm was used. Figure 7 - bottom shows the achieved height profile on a diameter of approx. 200 µm. The mean accuracy of the stroke using this un-calibrated system is achieved to approx. 10 nm.

It was found, that the uncontrolled open loop system has a tendency to oscillate after performing a height step. It is called ‘over shoot’ effect. For reducing this effect in an open loop system, the signal for the step jump was divided in two parts which one could refer to as “input shaping”. At the nominal trigger for the step only a share of the step height signal is sent to the piezo of the nFTS. After a time period that is halve of the oscillation time of the natural frequency of the nFTS the full step is performed. By this method, the amplitude of the tool oscillation after performing a step can be reduced by a factor 4 at minimum (cf. Figure 8).

Figure 7. WLI image of a 120x160 µm² structure (top) for testing the step height deviation.

height [nm]
\[ \text{distance [nm]} \text{ (on diameter 200 µm)} \]

Figure 8. AFM image of a 316.4 nm step without compensation (top) and with compensation.
Figure 9 shows an example of a DOE machined with nFTS. The white light interferometer image shows the topography of the center of a flat DOE with a diameter of 20 mm. The maximum step height is 316.4 nm. In contrast to DOEs machined by lithography, any step height between 0 nm and 316.4 nm can be achieved and therefore any kind of phase modulation can be obtained. The optical reproduction of the DOE in Figure 9 in the far field is depicted in Figure 10. It derives from the DOE if illuminated using a coherent light source with a wavelength of 632.8 nm. The non-uniform distribution of the intensity is assumed to be a consequence of the not fully calibrated nFTS system and the DOE calculation algorithm. A model for suppressing the systematic deviations for a calibration process and an advanced DOE calculating algorithm are under development. The advantage of the technology described will be the short manufacturing time of almost less than one hour including the design of the image to be depicted, calculating the DOE-structure and machining of the DOE. Therefore, it is applicable to a single piece production of individual DOEs at a relatively low price and it is easy applicable to industrial processes.

CONCLUSION
A novel diamond turning process has been realized enabling the fast and efficient generation of discontinuous diffractive patterns on metal substrates. It is based on a developed nano fast tool servo. The current system is designed for generating saw-tooth- (blaze) structures with a maximum step height of 500 nm. It exhibits an accuracy of approx. 10 nm in an un-calibrated system. It has been successfully shown, that this technology can be used to generate holograms by a diamond turning process. In contrast to typical FTS the developed nFTS has a simple system architecture and can be easily adapted to several ultra-precision machine tools. It was found that nFTS technology can act as a new key technology for several DOE applications. Further work will focus on advanced DOE calculation methods and machining technologies for multilayered DOEs that will be manufactured in several process steps. Those DOEs cannot be copied with justifiable means. Therefore, they are ideal for security applications.

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