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Influence of the rake angle on the surface formation during micro shaping of submicron optical structures in Au-layers

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Abstract
The manufacturing of discontinuous micro-optical structures in the submicron range by shaping processes places high demands on the accuracy and reproducibility. With diffractive optical elements (DOE), the requirements can be in the nanometre range. Lithographic and mechanical procedures compete to achieve these requirements with a high variety of shapes.
The mechanical production by ultra-precision machining (UPM) allows higher degrees of freedom and the manufacturing of optics with a higher efficiency. By comparison, lithographic processes ensure a reproducible accuracy. To eliminate this disadvantage, a further development of machine technology and process technology is necessary. For the mechanical production of planar diffractive optical structures, galvanic gold is an established material. In order to achieve the same results in structuring free-form surfaces on 5-axis machines, the machine kinematics and the tool guide have to be reconsidered. The lower the number of axes involved, the higher is the achievable accuracy. However, this reduction leads to variable rake angles and thus to variable chipping conditions in the sagittal plane. In particular, high process forces due to negative rake angles are suspected to cause profile deformations. Therefore, the influence of the varying conditions on the surfaces in the production of discontinuous micro-optical structures (blazed gratings) was investigated. Process forces, roughness, profile shape and tool wear were considered to understand the interactions and the development process. The studied structures have a height of less than 100 nm. Since the manufacturing of diffractive optics requires very large processing times, the wear is of major importance. Due to the manufacturing process the wear takes on a specific form. It has been shown that the tool guidance has a huge impact on the results.

Keywords: DOE, imaging diffractive optics, micro optics

1. Introduction

For the manufacture of DOE as shown in Figure 1, a plurality of methods is available. Here, lithographic and mechanical processes are in competition. Lithographic techniques generate the structures by the use of interference phenomena or by means of sequential direct writing [1]. Laminar gratings which are produced by interference lithography contain sinusoidal profiles and may feature high line densities.

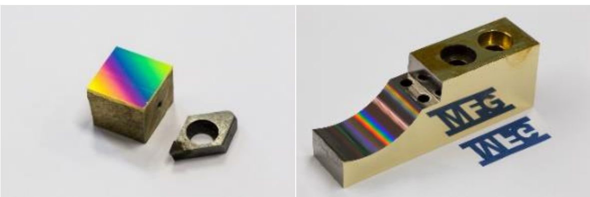

Figure 1. Exemplary plane and curved DOE produced at the IWF Berlin.

The major part of the intensity is reflected into the zeroth order and therefore cannot be used for the dispersion. A higher diffraction efficiency can be achieved with blazed gratings. Using this structure, the majority of the incident energy is diffracted in a defined order [2]. For the production of blazed gratings the selection of manufacturing processes is limited. With photolithographic manufacturing processes, a saw tooth profile can be approximated [3], but a higher efficiency is achieved by mechanically produced gratings. KÜHNE ET AL [4] have shown the possibility to produce quality DOE by UPM. The production by UPM allows more degrees of freedom than the lithographic production and permits structures that cannot be generated by the classical ruling process. For use in the visible range the tolerances are in the nm-range. The challenge rises once these structures will be created on curved surfaces; hence the diffractive properties should be reunited with the imaging properties of metal mirrors [5]. For a further increase of quality the machine kinematics and the tool guidance must be reconsidered.

2. Influence of the sagittal slope

The lower the number of axes involved, the higher is the achievable accuracy. However, this reduction leads to variable chipping conditions in the sagittal plane (Figure 2).

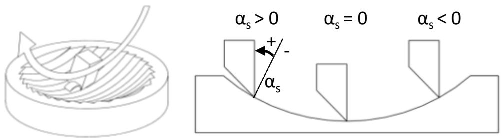

Figure 2. Schematic illustration of the production method and influence of sagittal trajectory.

Therefore, the influence on the surfaces in the production of blazed gratings is investigated. Process forces, roughness, profile shape and tool wear were considered in order to understand the development process and the interactions. The tests were carried out on a modified ultra-precision machine LT-Ultra MMC 1100. With regard to the nano-structuring, the machine is active vibration-decoupled and housed in a climatic chamber with a precision of ±20 mK. The measuring of shape and roughness was performed with a ZygoLOT NewView 5010 WLI and a Bruker N8 Neos AFM. The forces are detected with a Kistler piezo force-measuring unit. The obtained data allows the creation of linear forecast models at p-values below 1 ‰ level of significance.

2.1. Process forces

As clarified in Figure 3, changing the cutting conditions leads to a progressive increase in main cutting force as well as thrust force at progressively negative rake angle. With a chip thickness of one micron, as is usual when the nanostructures are being finished, the forces are not large enough to plastically deform the structures, even at high negative rake angles. With an increase of the chip thickness the force increases as expected linear. The linear regression rises significantly with the increase of negative rake. The slope is 10 mN/µm at a rake angle of 0 ° and 28 mN/µm at a rake angle of -25 °. With a negative rake angle the forces grow disproportionately with the chip thickness.

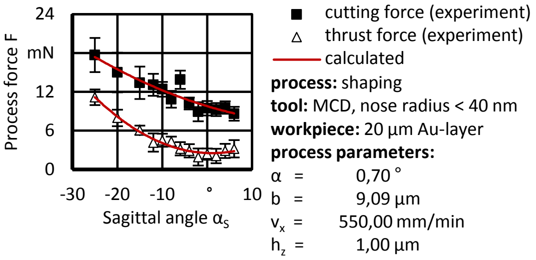

Figure 3. Process forces as function of sagittal slope for Au-layers.

2.2. Roughness

Unexpected is that the surface structure of Au, compared to other investigated materials, behaves virtually unaffected by the rake angle. The roughness remains in a range 2 nm < Rq < 3 nm (Figure 4) at a chip thickness of 1 µm. Even at elevated chip thickness the effect on the roughness is minimal (0,147 nm/µm). Only a combination of parameters from massive negative rake α_s and increased infeed h_z leads to a significant growing roughness. The absence of an adapted tool guidance in the sagittal trajectory has no negative influence on the surface structure in Au-layers, which benefits a reduction of machine axes which are involved in the shaping process. This behaviour differs from the other materials that were drawn into consideration for optical nano-structuring.

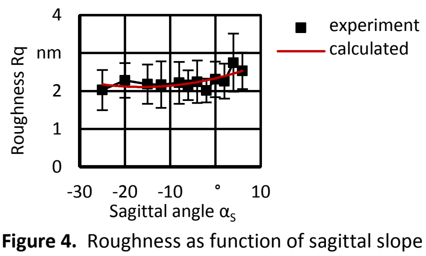

Figure 4. Roughness as function of sagittal slope for Au-layers.

2.3. Influence of wear

If wear occurs, the influence of the sagittal tool guidance cannot longer be neglected. The wear has a specific form due to the grating period b which is equal to the pickfeed. Starting from the rake face, it propagates into the flank face. Figure 5 shows an exemplary WLI measurement of the characteristic tool wear. This specific profile is replicated as a function of the slope of the sagittal trajectory geometrically into the structure. This means that even in case of damage in the nanometre range an unacceptable damage to the structure occurs. Figure 5 shows the increase of profile damage by the geometric transfer of the wear profile. With a small clearance angle, the structure is almost intact and functional in spite of tool wear.

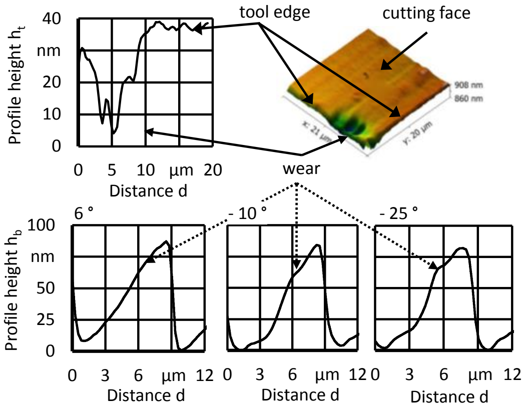

Figure 5. Wear profile of the tool edge (top), effect on the nanostructure (blazed grating) dependant of the sagittal slope (bottom).

3. Comparison to other materials

The parallel studied materials are RSA905 and amorphous NiP. The experimental procedure is absolutely identical for all materials. The process forces as a function of the rake angle of RSA905 are almost identical to those of Au. The roughness in this case behaves in correlation with the process forces (Figure 6). It increases significantly with the rake angle. The behaviour of the process force of NiP is qualitatively identical. However, as expected, the forces are significantly higher. The roughness is generally lower, but has a dependence on the cutting angle. Both materials show a significantly greater linear dependence of the roughness as a function of the chip thickness. The slope is 0,6 nm/µm for NiP and 0,71 nm/µm for RSA905.

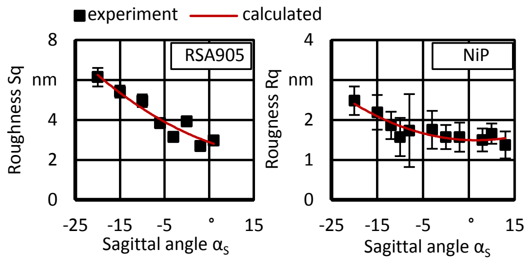

Figure 6. Roughness as function of sagittal slope for RSA905 and NiP.

4. Summary and Discussion

Regarding the surface quality, a production of imaging DOE without sagittal tool guidance is possible and provides higher system accuracy. In applications with wear susceptibility a sagittal tracking is advantageous. Using optimised cutting conditions a minimisation of wear as well as an improvement of surface quality can be achieved. In addition, effects of the wear can be minimised. Au is mostly independent of the machining conditions in particular.

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