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Mold machining and injection molding of diffractive microstructures

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ABSTRACT

Diffractive microstructures are used for many applications due to their unique optical functionalities, e.g. as security features on banknotes or documents. By developing more complex microstructures which almost cannot be copied, the protection against counterfeiting can be improved. This paper introduces a modified diamond turning process to machine such kind of functional microstructures. A fast-tool-servo assisted diamond turning process is presented, which enables machining of holograms consisting of diffractive microstructures with an overlaying pattern. The resulting structure is capable of shaping incident light into a defined intensity distribution. Such holograms could be used as security tags or be embossed in plastic packaging of valuable products. In order to make this technology accessible to mass production, replication of the microstructures by injection molding is essential. To investigate the replicability by injection molding, a blazed structure was diamond turned into a mold, identical to the basic structure of the holograms. Three optical polymers (polymethylmethacrylate PMMA, cyclic olefin copolymer COC, cyclic olefin polymer COP) were used for injection molding experiments to investigate the filling behavior of the mold and the replicated quality of the diffractive microstructure.

1. Introduction

Diffractive microstructures offer unique optical properties and are used for a wide variety of applications. Ranging from classical spectroscopic gratings and intra-ocular lenses to security features on banknotes, complex optical functionalities can be achieved [1]. Especially for security applications, constantly improved and highly functional microstructures are required to ensure a sufficient protection against counterfeiting. The complexity and thus the functionality of the microstructure largely depend on the kinematic options and precision of the machine tool. Common manufacturing processes for machining of diffractive structures are lithography, laser machining or diamond machining, which are distinguished by small structure sizes and short working wavelength [2].

Diamond machining processes have proven to be suitable for machining discontinuous microstructures and freeform surfaces. The high machining accuracy enables this process to machine advanced functional optical surfaces [3,4]. Typical diamond machined structures consist of mainly constant features in feed direction. One example are blazed gratings which can be a reliable alternative to electron beam lithography in terms of holographic fabrication [5,6]. Another example are Fresnel lenses. By using of non-rotational diamond cutting tools even multiple-focus micro Fresnel lenses can be machined with higher accuracy than lithography processes [7,8]. Both examples are having structure sizes ranging from a few hundred nanometers to several micrometers. More complex structures can be generated by an additional in-process tool movement, in order to adjust the depth of cut dynamically. Such a fast tool servo assisted turning process would enable the machining of even multi-leveled as well as freeform diffractive optical elements. The inexpensive, fast and extremely flexible machining process can be used also in the prototype fabrication for injection molding [9,10]. The technology used in the paper is based on a nano Fast Tool Servo (nFTS) as proposed by Brinksmeier et al. [11], which modulates the depth of cut in the nanometer range for machining of diamond turned holograms (DTH).

Previous research in this field has demonstrated that an excellent geometrical precision can be achieved by diamond turning [12]. However, in order to make this technology accessible to mass production, a replication of the structured surfaces is essential. In this paper, fundamental experiments are carried out to investigate the replicability of diamond turned blaze gratings by injection molding. Experiments were conducted using the different optical

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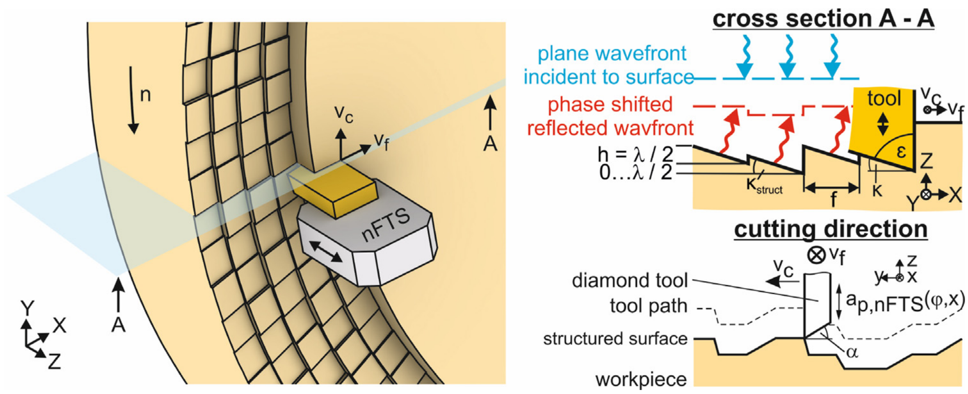

Fig. 1. Process kinematics for diamond turning of diffractive microstructures.

polymers (polymethylmethacrylate PMMA, cyclic olefin copolymer COC, cyclic olefin polymer COP). The filling behavior of the mold and the replicability of the diffractive microstructure were of primary interest and thus evaluated by measuring the structures with an atomic force microscope (AFM) as well as with a white light interferometer (WLI).

2. Machining of diffractive surfaces

The manufacture of the diamond turned holograms (DTH) is achieved by a face turning process, implemented on a *Precitech Freeform 3000* ultra-precision machine tool. Due to the local height levels, diffractive holograms are capable of modulating the phase of laser radiation to generate a defined intensity distribution (cf. Fig. 1 cross section A-A). As the local height levels are ensuring the functionality of the resulting holographic structure, the depth of the cut needs to be dynamically adjusted. Therefore, the classical diamond turning process is combined with a piezo driven nano Fast Tool Servo (nFTS) with a frequency of up to 10 kHz. The maximum stroke of the nFTS measures 350 nm and it is able to modulate the depth of the cut with a positioning accuracy less than 4 nm, which is required to achieve the high quality of the holographic structures. In combination with a spindle speed of $n = 100\,min^{-1}$, the nFTS is able to generate 2000 segments per revolution, each having a specific height level depending on their radial position φ on the helical tool path. The radial position of each segment is derived from the angular encoder of the main spindle, which is used as a trigger for initiating the nFTS movement.

The tool is a monocrystalline diamond with a wedge-shaped geometry, having a nose angle of $\varepsilon = 84^\circ$ and a structure angle $\kappa = 6^\circ$ (cf. Fig. 1 cross section A-A). This specific tool geometry combined with the process kinematics is generating the spiral-shaped blaze structure on the surface. The clearance angle α is limiting the maximal angle which the tool can generate while moving into the workpiece. To obtain higher structure accuracy the clearance angle α needs to be relatively large, in this case $\alpha = 20^\circ$.

There are several requirements regarding the workpiece material, in order to achieve diffractive optics with excellent surface finish. The material needs to be machinable by diamond turning and the resulting surface has to meet optical quality (i.e. roughness Sa < 10 nm). The functionality of holographic structures is highly depending on the contouring accuracy and a minimal burr formation. In former investigations, several nickel silver alloys, which have been proven to be machinable by diamond turning, were examined for applications in the field of visible light. Nickel silver shows a high hardness as well as no significant tool wear and thus, it is advantageous for machining of sharp edges. From a wide range of alloys with specific characteristics CuNi8Zn42Pb4Mn1 (N31) has been chosen, because of its excellent machinability. The relatively high percentage of lead (4%) leads to low cutting forces and little burr formation. Together with the formation of short chips, this results in significantly less tool wear and an excellent surface finish [12]. The high content of Zinc (42%) is also advantageous for diamond turning, inducing a better machinability and less deformations [13]. These improvements are resulting in less surface defects, a high contouring accuracy and lower roughness values (Sa = 5 nm on top of the optical effective surfaces of the blaze structure) [11]. The optical effective surface is the surface which is showing the provided structure angle κ as well as the specific height level and is reflecting the incident light in the intended way by shifting the phase of the reflected wave front (cf. Fig. 1 crossection A-A).

Table 1
Tool geometry and process parameters.

Cutting tool		Workpiece material	
Material	Monocrystalline diamond	CuNi8Zn42Pb4Mn1 (N31)	
Nose angle ε	84°	Process parameters	
Structure angle κ	6°	Feed f:	10 μm
Clearance angle α	20°	Depth of cut a_p:	2 μm
Rake angle γ	0°	Spindle speed n:	10 rpm

3. Mold machining

For the assessment of the replication process, continuous blaze structures without height modulation were diamond turned on an ultra-precision machine tool. Table 1 shows the process parameters as well as the material and geometry of the cutting tool. For cooling, a paraffin spray mist was chosen. As discussed in chapter 2, nickel silver N31 was adjudged to be the most suitable mold material.

Under these machining conditions, the blaze structure was transferred into the mold by diamond turning. In Fig. 2(a) the mold insert is shown. The surface topography of the blaze structure is shown in Fig. 2(b). A white light interferometer (Talysurf CCI HD, Taylor Hobson) was used to measure and evaluate the geometry of the blaze structure, which will be compared with the molded surfaces in chapter 4.

The surface topography is smooth and sharp edges can be detected, which are required for high performance optical applications. In Fig. 2(c), the surface profile A-B is shown. Based on this profile, the structure height *h*, the length of the optical effective surface *s* and the structure angle κ have been measured on each structure element. Afterwards, the average and the standard deviation were calculated over the measured values for each parameter respectively. In Table 2 the results of this analysis are listed. It can be seen, that the average structure angle equals 6.6°. This deviation from the desired structure angle $\kappa = 6^\circ$ is not decisive for the finally