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Evaluation of ultra-precision milling strategies for micro lens array mould inserts for the replication by injection-compression moulding

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Abstract
Micro lens arrays (MLA) are broadly used in a multitude of optical applications, whereas increasingly extended areas need to be structured. Furthermore, growing quantities of microoptical components require micro- and nano-replication techniques, such as injection moulding and injection compression moulding. Therefore, ultra-precision milling strategies for manufacturing of mould inserts have been evaluated regarding applicability, surface quality and processing time. Different milling strategies were investigated regarding processing time and resulting surface quality. Single flute diamond milling tools were used to mill the mould cavities in nickel-phosphorus (NiP) coating deposited on tooling steel. The experiments were conducted on a 5-axis ultra-precision milling machine and qualitative results regarding observed effects of the different strategies were evaluated. The achieved surface qualities were analysed and quantified using white light interferometry. Methods of ring, radial or spiral milling strategies showed different failure modes and shortcomings such as stepping, pin residues or long processing times. Using a method, where a specifically designed milling tool was immersed in a single step into the bulk material, best results were achieved and the processing time for each lens was reduced to a minimum. The quality of the MLA could be further increased by immersing the milling tool in a defined angle. It was observed, that the centering and radius of the diamond of the milling tool was a major factor. Conclusively, the results show that high quality tooling in combination with the applied milling strategy enables significant improvements in quality and costs.

Keywords: Ultra precision milling, micro lens array, molding, optical elements, micro manufacturing, micro- and nano-replication

1. Introduction

Polymer optics gain increasing importance in a multitude of applications, replacing traditional glass optics [1]. Due to technological advantages, free-form optics as well as micro-structured optical components can be fabricated at a significant lower price. For the replication of these optical components, injection molding has been proven to be an excellent method. An example for micro-structured optics are micro lenslet arrays (MLAs). For the fabrication of these polymer optical components, mold inserts have to be fabricated. Ultra-precision milling (UP-Milling) is one of the most common technology to fabricate these optical mold inserts. UP-Milling combines very high accuracy and optical surface quality in one process. Since MLAs consist of hundreds to thousands of small micro lenslets, the fabrication of the mold inserts is challenging. The work presented in this paper investigates different milling strategies for the fabrication of a MLA mold inserts. Thereby optical surface quality as well as processing time are the most important factors. Literature shows, that UP-Milling is a suitable method for the fabrication of MLA mold inserts [2]. In contrast to other research, this work focuses on the fabrication of each individual lenslet, not the full MLA.

2. Methods

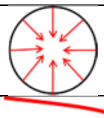
The machining of tool steel with diamond tools is only possible with special equipment due to significant wear of the diamond. Nickel-phosphorous (NiP) is the most used substitute material, combining high hardness with good machinability. The experiments in this work were performed in NiP-coatings provided by CZL Tilburg (NL) on tool steel. Diamond milling tools with various radii were used for the milling experiments ranging from 0,2 mm to 1 mm. The diamond tools were provided by Contour Fine Tooling (NL). For the UP-Milling a Precitech Freeform 700A ultra-precision machine was used. The machine is equipped with a Levicron air bearing spindle and five controlled axis, allowing a multitude of machining setups. During the cutting process the work piece is cooled using isoparaffin applied through a minimum quantity spray nozzle. The machining parameters were set to the following parameters.

Table 1 Processing parameters used in the UP-Milling process

Spindle speed [1/min]	75 000
Feed rate [mm/min]	2.5-25
Cooling lubricant	Isopraffin
Workpiece Material	NiP
Milling tool radius [mm]	0.2 – 1.0

Short processing time is an important factor for the quality of the MLA, due to induced deviations caused by temperature drifts as well as cost benefits. Hence, the processing time for each individual micro lenslet was measured. For optical applications the surface roughness needs to be below Ra= 25 nm. The resulting surface quality was analysed using wight light interferometry (WLI, Veeco Wyko NT9100). Four different milling strategies wered used to fabricate the individual micro lenslets and are described in Table 2.

Table 2 Milling strategies investigated in the experiments

Ring milling	Milling of circular rings and reducing the diameter after every ring. Simoultaneously adjusting the depth of cut	
Radial milling	Starting from the outside and milling direct lines towards the center	
Spiral milling	Insert the milling tool in a spiral like movement	
Vertical insert	Vertical immersion of the milling tool with no further movement	

3. Results

The investigated milling strategies resulted in movement specific surfaces. Using ring milling or radial milling, a distinct line and steps become visible. Using the ring milling strategy, the line occurs at the position where the milling tool repositions after finishing one ring. The resulting surface roughness is Ra = 85 nm at a processing time of 6 min. Using radial milling, a line occurs at the end of the process, when a previously milled area is passed again. Using this strategy, the surface roughness improves in the center since this area is passed through more often. The resulting surface rougness is Ra = 71 nm at a processing time of 10 min for each lens. Both strategies create insufficient surface qualities and lead to disproportionate long machining times.

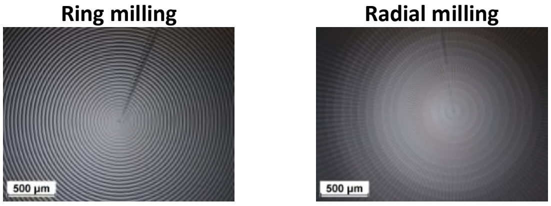


Figure 1 Imagies of the resulting surface after ring and radial milling

Further investigations applied a spiral milling strategy. Thereby the milling tool inserts in a spiral-like movement. The resulting surface roughness is Ra = 68 nm at a processing time of 1 min. Figure 2 shows an extract of a micro lenslet array using a spiral milling movement. The surface quality can be improved by reducing the increments per revolution but the processing time increases significantly.

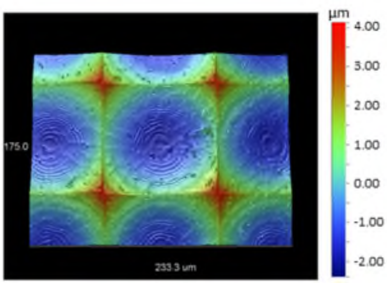


Figure 2: Spiral tool immersion

The fourth milling movement was a vertical immersion of the milling tool. Thus, the resulting lenslet matches the shape of the tool. Thus, the quality of the tool is of utmost importance. The radius of the cutting edge needs to have the exact same radius as the desired lenslet radius and a low waviness. Furtheremore the centering of the diamond on the milling tool has to be accurate. Immersing the milling tool at a 0° angle, material remains in the center of the micro lenslet, which can be seen in the WLI measurements in Figure 3. This is due to the fact that the position of the diamond always deviates from the center, leading to a positioning of the milling tool in an angle >20° in regard to the workpiece. However, the angle needs to be larger if the depth of the lenslet increases. Using the vertical immersion milling movement, the resulting surface roughness is Ra = 9 nm with a processing time of about 1 sec for each lenslet. Feed rate during the immersion is set to 2.5 mm/min.

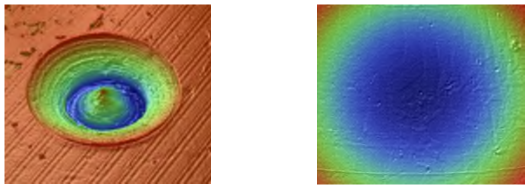


Figure 3 Resulting micro lenslet when using the vertical insert milling with the milling tool at 0° and 20°

Since the vertical insert strategy shows the best results, this milling movement is preferably used to create a MLA mold insert. For large scale demonstration, a micro lenslets array with a lenslet pitch of 127,5 µm and an surface radius of 1 mm was designed. The structured area is 13x15 mm resulting in 12 000 lenslets milled into the mold insert. A picture of the final mold insert can be seen in Figure 4. While a total processing time of 5 h could be achieved and the array could be milled using a single diamond mill, tool wear becomes a limiting factor for upscaling the total count of lenslet and necessitates quality control of the achieved structures.

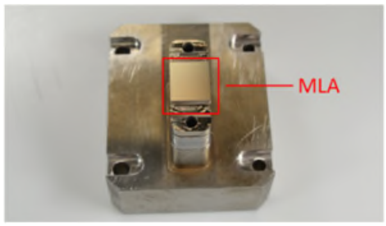


Figure 4 Mold inserts with MLA

5. Summaray

The paper presents the mold fabrication for a MLA by means of UP-milling, focusing on the milling strategies for micro lenslets. Therefore four different milling movements have been investigated. The best results were obtained if the milling tool was verticaly immersed at an angle of 20°. This strategy achieves high accuracy and surface qualities <10 nm, but the results in regard to the form factor depends strongly on the quality of the diamond milling tools.

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