Investigation on Resulting Form Errors of Precision Ground Optical Moulds with Respect to Tool Path Compensation

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Abstract

Main topic of this paper is the analysis of error sources in precision grinding process affecting the resulting form accuracy of ground moulds. Hereby, static and dynamic machine tool properties and behaviour during the cutting interactions, fixturing and alignment issues, and the kinematical process setup as well as process forces lead to residual form deviations. These form deviations have been measured and compensated by a suitable in-situ measurement and tool path compensation system.

1 Introduction

The mass production of complex shaped optical glass lenses with high requirements on functional performance needs cost-effective, economic precision glass moulding processes. Therefore, the manufacturing of mould inserts with high requirements in form accuracy and surface quality have to be done by deterministic machining processes on multi-axes ultra-precision machine tools (UPM). Typically, precision grinding processes with suitable fine-grained diamond abrasive tools with well-known tool dimensions are applied for the machining of high-temperature resistant, hard-to-machine mould materials, like for e.g. binderless tungsten carbide. Nevertheless, the manufacturing of precision moulds requires fundamental knowledge of the applied machining processes and tool behaviour [1] [2].

Deterministic manufacturing in this sense means several machining cycles beginning with tool and workpiece alignment and positioning, tool radius determination and tool path generation, precision grinding, and ending with form deviation measurements for tool path compensation for the next machining cycle. Fig. 1 describes a step-by-step procedure for achieving the required form tolerance of the mould by ultra precision grinding. Prior to machining, the grinding wheel and the workpiece must be adjusted in the machine tool coordinate system. After balancing the grinding tool has to be dressed and its geometry must to be determined for creating an NC-tool-path.

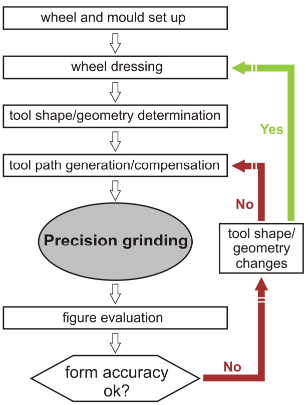

Fig. 1: Flow chart for precision grinding of optical moulds

Form evaluation of the ground surface is necessary for determining the form deviation of the mould. If the shape tolerance is not met, the NC tool path has to be modified for compensating the residual errors. These errors describe the deviation in the position of the grinding tool from the theoretical required value to produce the workpiece shape within the specified tolerance. Here, the investigation of error sources of the machine tool, machining process and applied grinding tool help to predict and optimize the resulting part shape accuracy.

2 Manufacturing and Error Compensation

The grinding of the moulds was performed on a 5-axis ultra-precision machine tool *Nanotech 500FG* (Moore Nanotechnology Systems) with an aerostatic high precision grinding spindle. The workpieces are 15 mm diameter cylindrical blanks from binderless tungsten carbide. Fig. 2 shows the experimental setup for the parallel grinding process. Here, the pin-type diamond grinding tool was moved along the workpiece, with an inclined angle $\alpha = 45°$. Before grinding, the grinding tool and the workpiece have been aligned to each other within the centre of rotation of the main spindle.

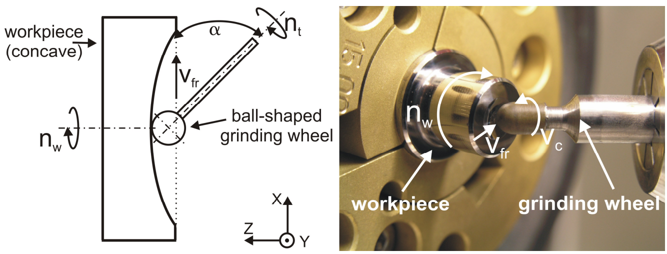

Fig. 2: Kinematics and machining setup of the applied grinding process

The workpiece was aligned by a precision adjustment and clamping device. Both, workpiece and grinding tool achieved an axial and radial run-out accuracy (concentricity) of approx. 0.200 µm. The centre alignment of the grinding tool was realized by a three-point-touching-procedure with a ceramic calibration ball (peak-tovalley PV = 0.080 µm). Here, a horizontal and vertical alignment accuracy of less than 0.500 µm was obtained with respect to each other.

During the grinding process the grinding tool rotational speed n_t and the workpiece rotational speed n_w were kept constant at n_t = 30'000 min^{-1} and n_w = 150 min^{-1}, leading to a maximum cutting velocity of $v_c \approx 7.85$ m/s. The depth of cut a_e and radial infeed velocities v_{fr} varied in a range of a_e = 1.0 – 0.1 µm and v_{fr} = 1.0 – 0.1 mm/min, according to roughing and finishing procedures. A multi-layered, resinoid bonded diamond grinding tool with grain size d_g = 7 µm was applied.

3 Resulting Shape Accuracy

After the grinding process the shape accuracy of the ground mould was measured with a tactile in-situ, LVDT-based measurement system with a lateral resolution of 10 nm. The calculated form deviations regarding the desired spherical figure and radius were used for the generation of an error compensated grinding tool path. Starting with a measured shape accuracy of PV = 1.08 µm after the first grinding step, the part form deviation could be machined to PV = 0.81 µm after the 4th grinding cycle and to PV = 0.41 µm after the 8th grinding step (scan length 5 mm, see fig. 3).

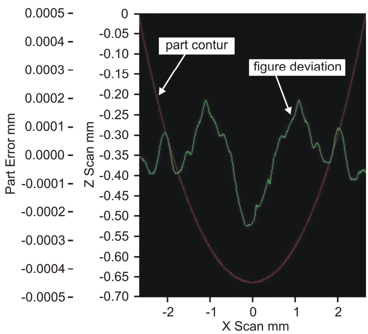

Fig. 3: Shape accuracy of a ground mould after 8 compensation steps

4 Error Budget Assessment

Errors of manufacturing processes can be classified into two categories, quasi-static errors and dynamic errors. Quasi-static errors are those errors between the tool and the workpiece that are slowly varying with time and related to the machine tool structure, including geometric errors of the machine components and structure, fixturing errors, kinematic errors, instrumentation errors and errors induced by thermal distortions as well as tool wear [3]. Dynamic errors are caused by sources such as spindle error motions, vibration of the machine structure, controller errors and cutting forces.

Especially the quasi-static errors affecting the figure accuracy of machined parts do have high potential to be compensated by suitable in-situ measurement systems and tool path compensation procedures. Therefore, possible error sources have been defined and analysed regarding the applied UPM, grinding process setup and grinding tool. Table 1 shows selected error source values from the machine tool manufacturer, the described setup and alignment measurements and analysed process data with estimated relevance for the present machining process.

Table 1: Specific error source, values and potential for tool path compensation

specific error sources		**PV value [µm]**	**compensation potential**
geometric machine tool X-axis movement error	with X-axis travel of 5 mm	0.010	high
	with Z-axis travel of 1 mm	0.005	high
fixturing errors (alignment/positioning)	grinding tool vs. workpiece	0.500	low
grinding tool errors	radius	10.000	low
	form waviness	1.000	very low
thermal distortion (machine tool environment, cooling fluid)		0.050	very low
spindle errors	workpiece spindle	0.050	high
	grinding tool spindle	0.010	high
grinding tool deflection (at normal grinding force $F_n = 0.1$ N)		0.020	low

5 Conclusion

In conclusion, a procedure for precision grinding of tungsten carbide moulds was developed and analysed regarding machine tool and grinding process specific error sources. In practical style, several in-situ measurements and tool path compensation steps lead to a final form deviation of approx. 0.4 µm. Here, most of the described error sources, quasi-static and dynamic, show high potential for error compensation. But, especially grinding tool and workpiece fixture and alignment errors as well as tool figure errors need to be eliminated for higher workpiece shape accuracies.

Acknowledgements

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