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# Influence of machining errors on form errors of microlens arrays in ultra-precision turning

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ABSTRACT

Ultra-precision turning is widely used in machining microlens arrays. Machining errors have an effect on the form accuracy of the whole microlens array, but they have not been fully studied, especially the effect on the optical performance. A machining error model of microlens arrays is built to analyse the co-ordinate distortions and form errors easily based on multi-body system theory and a homogeneous transformation matrix. The simulative and experimental results verified the influence of three major machining errors (tool alignment errors ($\Delta x$, $\Delta y$), tool nose radius error ($\Delta R$) and squareness error ($\Delta \theta$) from the proposed approach. Through the simulation and experimental approach, this study describes the distribution of the form errors as axisymmetric; the form error of the centre part of the row and column cells is minimal, whereas that of the diagonal cells is the maximum. The optical performance of the cells has the same correlation as the form errors. Based on the above study, a horizontal off-centring machining method is proposed to achieve high form accuracy and uniform optical performance.



## 1. Introduction

Microlens arrays, a type of structured-feature freeform surface, are important optical elements. They are increasingly applied in many fields, such as beam shaping [1], uniform illumination [2] and high performance imaging. For example, microlens arrays have been used as the core part in Shack–Hartmann wavefront sensors to achieve light spot and optical performance analysis [3]. In addition, microlens arrays are also applied in bionic compound eye systems to achieve a wide view field in miniaturization and realize integral imaging, super resolution and high speed tracking [4,5]. Imaging applications require higher quality shape accuracy and uniformity.

Several studies have developed high-efficiency and high-accuracy manufacturing methods. The common optical manufacturing methods are thermal reflow of photoresist, printing, laser direct writing, focused ion beam etching and nano-imprinting lithography [6–8]. These methods can be employed to produce microlens arrays with good performance. However, a long processing time is required, and it is difficult to control the precision, so it is hard to achieve the required uniformity over a large area. Ultra-precision machining is the most effective method to make microlens arrays with high form accuracy. Ultra-precision grinding [9] is capable of machining microlens arrays with very fine surfaces and has a relatively long process cycle. Diamond micro-milling [10,11] can be used to machine microlens arrays efficiently in a one-by-one cell, but the machining cost is very high. With regard to this, diamond turning [12,13] has become a research focus in machining microlens arrays because it can achieve non-rotational symmetrical components with high efficiency and high accuracy by means of fast tool serve and slow tool servo.

Due to the geometric complexity and high accuracy requirement of the microlens array, there are several challenges in the manufacturing of ultra-precision microlens arrays with sub-micrometre form accuracy and surface finish in the nanometre range, which still need to be studied. The selection of the optimal cutting parameters (depth of cut, feed rate, spindle speed, surface speed and driving frequency of the FTS) in ultra-precision turning of microlens arrays have been researched. To et al. [14] investigated the effect of the cutting conditions, such as the depth of cut, feed rate, spindle speed and surface speed, on the microlens array in ultra-precision diamond turning with a fast tool servo (FTS) and found the optimal surface roughness and surface profiles. Yu et al. [15] studied the optimal selection of the machining parameters, including the spindle speed, sample number, feed rate and tool geometry, in fabricating a micro-structure surface. Hong et al. [16] indicated that the quality of the surface depends mainly on two important factors: the cutting speed (or spindle speed) and the driving frequency of the FTS.

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Some researchers studied the compensation of the tool radius, sliding errors and tool setting error. Kwok et al. [17] proposed a tool radius compensation method for improving the form accuracy of the microlenses in ultra-precision machining with a fast-tool-servo (FTS) system. Yu et al. [18] analysed and compensated the profile error of the micro-structure surface, which was caused by the sliding error and the dynamic error of the FTS system. Chen et al. [19] proposed a tool setting error compensation method for the fabrication of an AMLA model. The form accuracy and surface roughness of each lens of the AMLA were less than 0.2 μm and 5 nm, respectively. Gao et al. [20] proposed a tool setting method for tool replacement in the fabrication process of a microstructure array over a roll workpiece using a force sensor integrated FTS on a precision lathe. The new tool can be set with sub-micrometre accuracy based on the identified position of the tool tip with respect to the reference area.

Researchers have also focused on the development of the simulation and evaluation system to guide the actual machining. Zhou et al. [21] established a simulation system, including a cutting force model, platform movement model, fast tool servo model and spindle movement model, which performs guidance for the machining of the micro-structured surfaces. Kong and Cheung [22] established an integrated platform for the design, fabrication, and measurement of ultra-precision, micro-structured, freeform surfaces. Optimal machining parameters, the best cutting strategy, and optimization of the surface quality can be obtained without the need for conducting time-consuming and expensive cutting tests. You et al. [23] proposed a contour error evaluation system to help users determine a suitable step-size of the tool for the path data according to the machining conditions and their expected level of surface quality by calculating the geometric contour errors in relation to variations in the intervals between tool paths. Yu et al. [24] proposed an optimized tool path generation method for FTS diamond turning of micro-structured surfaces, which considered the tool nose radius compensation, the optimized cutting conditions and the tool geometry, which is obtained by the surface profiles simulation and the FTS dynamics compensation. Neo et al. [25] developed a novel surface analytical model to evaluate the cutting linearization error of all cutting strategies for surface generation and optimized the number of cutting points to meet the accuracy requirements for the constant-angle, constant-arc and hybrid (HCAA) methods.

The current research studies have made great advances in accurately machining microlens arrays, but they conducted verification experiments and evaluated the profile accuracy or form accuracy by selecting only one or two cells arbitrarily. However, in our study, we found that each cell in the different positions of the whole coordinate has different cutting statues. The form errors of different cells caused by the same error or parameters will be different. Therefore, it is not appropriate to evaluate the whole array's accuracy through arbitrarily selecting one or two cells. At present, there is little research on how the machine errors influence the form accuracy of the whole microlens array. In addition, the main machining errors have significant effects on the form accuracy of the components in the turning process, but we still do not know how these errors affect the form error or the optical performance of the whole microlens array or each cell. If we know these influence regularities, we can reasonably select the appropriate cell to evaluate the accuracy of the microlens array or recognize the error that affects the form error according to the measurement result and can compensate the errors quickly. There is also little research on the influence regularity of the machining errors on the form accuracy.

In this study, a machining error model was proposed for the ultra-precision turning of the microlens array. Through the simulative and experimental validation, the effects of the tool nose radius, the squareness and the tool alignment errors on the coordinate distortions and form accuracy of microlens arrays have been explored. An effective ultra-precision turning method was also proposed to improve the microlens uniformity of form accuracy and optical performance based on the error model and the influence regularity.

## 2. Machining error model of the ultra-precision turning machine

The configuration of the ultra-precision diamond turning machine in this work is a traditional T-structure machine with three axes, as shown in Fig. 1. It has two translational *X* and *Z* axes and one rotational *C* axis. It is a slow tool serve system, where the tool system is mounted on the *Z* axis and moves along the *Z* axis. The workpiece is mounted on the *C* axis, which rotates precisely at high speed and simultaneously moves along the *X* axis. The cylindrical coordinate method was adopted to design the spiral machining path, and the cutting tool nose radius was compensated according to the shape of the workpiece in diamond turning [26,27]. The multi-body system theory and homogeneous transformation matrix were used to describe the motion error modelling of this machine configuration [28].

The errors modelling of the microlens array was established based on the flowchart of Fig. 1. The ideal machining path points were generated according to the surface characteristics and machining parameters of the microlens array. The actual machining path points were obtained considering the motion errors modelling. Then, the coordinate distortions plot was calculated from the difference between the ideal and actual machining paths. The form error changing trend of each cell can be described by this plot indirectly. By comparing the ideal surface to the actual machining path, the distribution of the form error and peak-to-valley (PV) value were obtained, where the PV value of form error was described by the subtraction of the corresponding *Z* value.

There are 25 types of machining errors for this configuration, including the alignment and tool nose radius errors of the cutting tool and the geometric errors of the machine tool. The geometric errors have been simplified into 11 error terms [28]. For these errors, the influence quantity of each error on the form error was investigated, as shown in Fig. 2, where $\Delta R$, $\Delta x$ and $\Delta y$ denote the tool nose radius error, tool alignment error in the *X* direction and tool alignment error in the *Y* direction, respectively, $\Delta\theta cx$ is the squareness error between the X axis and the *C* axis, $\Delta\theta zx$ is the squareness error between the *X* axis and the *Z* axis, *THx* and *THz* are the roll and yaw of the *X* axis, respectively, *Tcx* and *Tcy* are the radial run-out errors in the X direction and the *Y* direction, respectively, *THcx* and *THcy* are the yaws of the spindle axis about the *X* axis and the *Y* axis. According to the demand of the practical machining and machine precision, the tool alignment errors are less than 0.001 mm, the measurement error of the tool radius is less than 0.005 mm,the run-out and the yaw of the spindle are less than 0.00005 mm and 0.0003°, respectively, and the position error and yaw are less than 0.001 mm and 0.001°, respectively. In general, the value of each error adopted 0.001 mm or 0.001° in Fig. 2. For the ultra-precision machine, the spindle was usually high accuracy, and errors can be ignored. The comparison results prove that there are three major errors for form error, including (1) tool alignment errors ($\Delta x$ for the tool alignment error in the *X* direction and $\Delta y$ for the tool alignment error in the *Y* direction), (2) tool nose radius error ($\Delta R$) and (3) squareness error between the *X* axis and the *C* axis (squareness error for short, $\Delta\theta$). Therefore, these three errors were considered in the following sections.