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Novel selection system of ultra-precision machining tool for optical lens

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Abstract
The machining profile will always deviate from the designed profile, due to the finite tool radius of diamond turning tool. This deviation would occur theoretically before the commencement of actual machining process and introduce error in ultra-precision machining. Conventionally, tool path design will try to minimize the form errors which induced by the finite tool radius (FETR) geometrically. However, for optical components, the best geometrical approximation does not always match the best optical approximation. Thus, merely improving the form accuracies might not be an effective mean to attain a designated optical requirement which would be testified by comparing the designed profile with the measured profile. The measurement would be achieved by using a high precision interferometer. The optical lens would be machined again using tools with reduced tool radius, if the machined profile does not satisfy with the requirements. As tools with smaller radii are more vulnerable to tool wear, such tool will cause larger form errors. Thus, the optimisation process to look for an appropriate tool through trial and error is inevitably time-consuming.
To this end the impact of FETR should be predicted and a guideline on selecting a suitable tool to machine an optical lens should be developed for saving time. In this paper, a novel selection system of single point diamond tool for ultra-precision machining of optical lens is proposed. By taking into account the FETR, this system will generate simulated machining profiles for different tools from a designed profile and then simulate the optical performance of these machining profiles based on an optical ray-tracing model. With the help of the ray-tracing model, the wave-front aberration of a simulated focal spot would be estimated. The optimal diamond tool would be selected based on two criteria. It must be able to produce a focal spot with an acceptable amount of aberration while the tool radius should be the larger the better. Based on this proposed selection system, the machining effect of the optical lens can be predicted and the trial-and-error cycle can be shortened.

Keywords: ultra-precision machining, optical lens, adaptive selection

1. Introduction

There are normally two non-spherical surfaces in the diffractive-refractive hybrid objective lens (DHOL) which is compatible with multi-type optical discs, i.e. the Blu-ray Disc (BD) [1], China Blue High-Definition Disc (CBHD) [2], Digital Video Disc (DVD) [3] and Compact Disc (CD). One is the non-spherical diffractive-refractive hybrid surface with a large curvature, called "S1" in this study, while the other is a normal hybrid aspherical surface with a slight curvature, called "S2" (see Fig.1). Two sets of high precision optical surfaces need to be machined. Although both surfaces of the DHOL can be designed and optimized accurately with powerful optical software [4], the realization of all the required optical properties demand machining of such surfaces with a form error much less than 100nm. When the machining conditions (such as the material of the DHOL and the geometry of the single point diamond turning tool) and the design data of the DHOL are fixed, the optical deviations of the aspherical surface are mainly caused by the ultra-precision machining process that can be quantified by the residual form error compensation [5], while the optical deviation of the harmonic diffractive phase structure can be quantified by dimensional measurement of the surface relief pattern [6]. The quality of the DHOL determines the precision of the focal spot, at which the radio frequency (RF) signal is generated to reproduce the information encoded on the optical disc. Therefore, in this study a novel evaluation method in ultra-precision machining of the DHOL has been proposed to ensure that the DHOL generates desirable focal spots with high quality for each disc format.

The rest of this paper is organized as follows. The evaluation principle is proposed in Section 2. The experimental evaluation result is discussed in Section 3. Finally, a conclusion is given in Section 4.

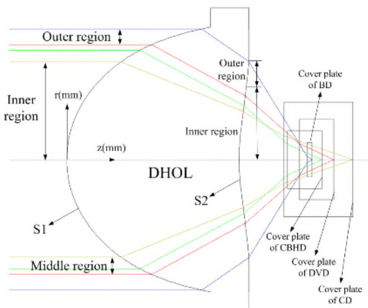

Figure 1. Optical layout of the DHOL with four focal lengths.

2. Evaluation of machining profiles

We can calculate the machined surface profile based on the designed DHOL surface profile and the corresponding tool-path expressed as reference points. As shown in Fig. 2, a half round tool with nose radius R is used. Then the horizontal rotation angle θ_H and the turning increment of the tool δ_r are set as variables. The included angle θ_I and the reference points of the tool set are either "Front Point" or "On-axis Tip". The $z_1(r)$ represents the designed surface profile and $z_2(r)$is the tool path. Then the machined surface profile $z_3(r)$ can be finally deduced from $z_1(r)$ and $z_2(r)$. The aims of our optimization process is to ensure that any point C on $z_3(r)$ can overlap or be mostly adjacent to the corresponding point A on $z_1(r)$, while B is the related reference point on $z_2(r)$.

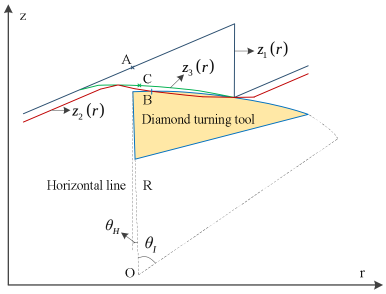

Figure 2. The machined surface profile.

When the parameters R, θ_H and δ_r are varied, the difference between $z_1(r)$ and $z_3(r)$ is evaluated by two factors. One factor is the average distance (*Dist*) in the same domain as shown in equation (1), while the other factor is the percentage of the special points (*SPs*) defined as the point with a larger distance than the *Dist*.

$$Dist = \frac{1}{R}\int_0^R \left| z_3(r) - z_1(r) \right| dr \qquad (1)$$

According to equation (2), the theoretical roughness h is related to the turning increment of the tool (δ_r) and the radius of the diamond turning tool (R). Usually the h is pre-set, so we can safely assume that the *Dist* is mainly affected by two parameters, radius R and the horizontal rotation angle θ_H.

$$h = \delta_r^2 / 8R \qquad (2)$$

3. Experimental results

In our experiments, we set the diamond turning tool radius R increases from 0.005mm to 0.05mm with the increment of 0.005mm, and set the rotation angle θ_H varies from -5 degree to 5 degree with 1 degree increment. The step depth of the harmonic diffractive phase structure is 0.002μm. Then the average distance (*Dist*) can be calculated according to equations (1) and (2). Fig. 3 shows the variation tendency of *Dist* under different R and θ_H values.

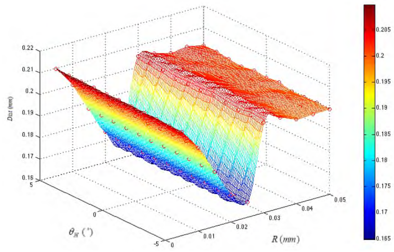

Figure 3. The change of the *Dist* with R.

From Fig. 3, *Dist* is smallest when R is around 0.025mm and θ_H is barely affected. The percentage of the *SPs* is calculated for R varying from 0.02mm to 0.03mm in 0.001mm increments and θ_H varying from -5 degree to 5 degree in 1 degree increments to double check if the minimum value of the percentage can be achieved in the same situation as *Dist*. The results are shown in Fig. 4.

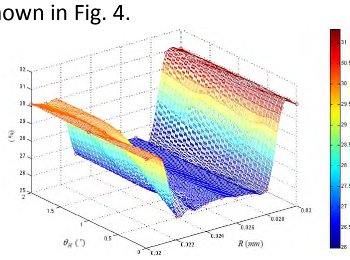

Figure 4. The change of the percentage of the SPs.

From Fig. 4, the percentage of the *SPs* is smallest when R equals to 0.028mm and θ_H equals to 2 degree.

The revised ray tracing algorithm includes two calculation stages. In the first stage, the machining profile is fitted by the general polynomial surface in order to import the machining profile into the optical design software "Zemax" for further analysis. In the second stage, the total optical wavefront aberration is calculated to compare with the original design. Fig. 5 shows the change of the wavefront aberration under different R and θ_H values. The wavefront aberration varies mildly among the data groups, in which the peak to peak difference is about 5%. Therefore, the different selection of diamond tools would not pose significant changes of the wavefront aberration onto the simulated machining profile.

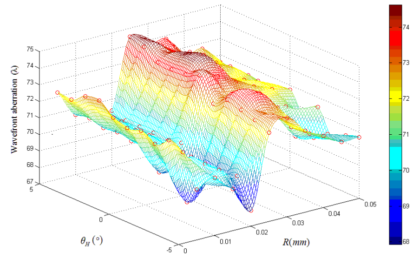

Figure 5. The change of the wavefront aberration .

4. Conclusion

In this paper, a novel evaluation and compensation method for ultra-precision machining of hybrid lens is proposed. During the evaluation process, the diamond turning tool was first chosen and then the machining effects on the optical profile generated were evaluated, both theoretically and experimentally.

5. Acknowledgement

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