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Nanometer precision fabrication for optical surfaces

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Abstract

The fast development of technology results in increasing demands on nano-precision optical surfaces in fields of lithography, synchrotron radiation, space observation and inertial confinement fusion (ICF). As the requirements on equipments performance are continuously rising, the surface accuracy and roughness of optical components need to be further improved, which almost hit the theoretical physical limit. The highly increased demands not only bring tough challenges for optics fabrication, but make it the frontier in the nano-precision fabrication area. Through the development of conventional polishing and computer controlled small tool polishing technique, the technology of optical manufacturing has evolved to controllable compliant tools polishing, which is represented by Magnetorheological polishing (MRF) and Ion Beam Figuring (IBF). The polishing tools of these latest developed techniques could be controlled flexibly, which enhances the manufacturing adaptability to aspheric surface curvature and the long-term stability of removal function. By utilizing the self-innovated controllable flexible polishing technology and facilities, National University of Defense Technology has realized nano-precision fabrication of typical optical surfaces and provided strong support in manufacturing technology to national science and technology projects.

Keywords: nanometer precision fabrication; optical fabirication; controllable compliant tools polishing; magnetorheological finishing; ion beam figuring

1. Introduction

Modern optical components have typical features such as large aperture, sub-nano accuracy, complex form and low surface damage; they are widely used in areas of lithography, synchrotron radiation, space observation and inertial confinement fusion. MRF, IBF and CCOS machining process, named as Controllable Compliant Tools Optical Manufacturing (CCTOM) are developed and applied to fabrication of nanometer precision optics.

2. Key Research Issues in Nano-Accuracy Optical Manufacturing

2.1. Stable and Controllable Material Removal in Nanometer-Scale

The ability to remove material in atomic/molecular level is of vital importance to achieve nano- or subnano- precision, however, the atomic relocation one by one using atomic force microscope will be too time-consuming to utilize [1]. In respect of manufacturing, material removal in atomic/molecular level and high machining efficiency are both requisite.

MRF can remove material due to shear forces exerted onto the workpiece by the MR fluid. The polishing area is modeled based on the Bingham fluid theory. By analyzing the shear and compress stress and velocity within the area, the material removal rate can be formulated as follows [2]:

$$\frac{\partial}{\partial \overline{x}}[\overline{h}^3\overline{F}_2^a(\frac{\partial \overline{P}}{\partial \overline{x}})]+\frac{1}{4\Lambda^2}\frac{\partial}{\partial \overline{z}}[\overline{h}^3\overline{F}_2^a(\frac{\partial \overline{P}}{\partial \overline{z}})]=-\frac{\partial}{\partial \overline{x}}[\overline{h}\frac{\overline{F}_1^b}{\overline{F}_0^b}]+\frac{\partial \overline{h}}{\partial \overline{x}} \tag{1}$$

The material removal in IBF is usually investigated based on Sigmund sputtering theory, the energy consumption in removing material in atoms is formulated as [3]:

$$E=\frac{\varepsilon}{(2\pi)^{3/2}\sigma\mu^2}\exp(-\frac{Z^2}{2\sigma^2}-\frac{X^2+Y^2}{2\mu^2}) \tag{2}$$

The material removal model is constructed based on the above two equations and validated by experiments. Parameters that determine the removal rate are identified and controlled accurately, thus material removal in nano-scale/sub-nano-scale is realized.

2.2. Controllable polishing technique with compensation on complex form surfaces

It is known that the amount of material removal, $E(x,y)$, is the two-dimensional convolution of material removal function, $R(x,y)$, and the dwelling time, $\mathrm{T}(x,y)$.

$$E(x,y)=R(x,y)*T(x,y) \tag{3}$$

In machining, the removal function should keep constant in spite of time and space variation in order to accurately compute the dwelling time. However, in transition of planar to free form optical surfaces, the change caused by surface curvature on removal function is nonlinear, which affect the accurate solution of dwelling time. The reasons for such changes are due to the projection distortion and edge effect, which must be compensated in computing algorithm. A dynamic model of removal function has been constructed in response to the curvature change in machining for both MRF and IBF.

In IBF, the nonlinear response of material removal rate to target distance, incidence angle and surface curvature has been established and validated in experiment, as shown in Figure 1 [4]:

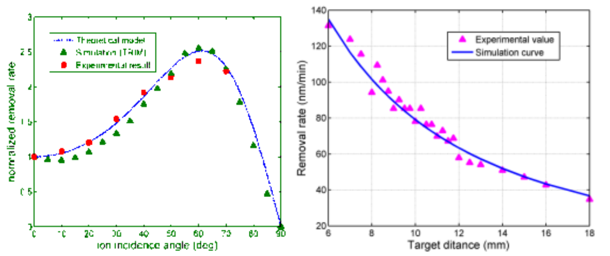

Figure 1. (a) material removal rate vs incidence angle (b) material removal rate vs target distance

In MRF, due edge effect, removal function shows great difference at the optics edge, the relations between ideal and actual removal function can be established by experiments, as shown in Figure 2[5].

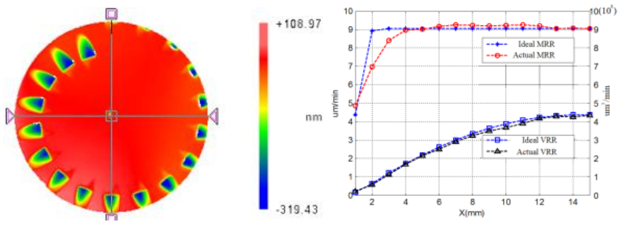

Figure 2. (a) edge effect in MRF (b) relations between ideal and actual peak/volumetric removal rate

Given the above nonlinear relations, the dynamic removal function can be computed and replace the constant removal function, $R(x,y)$, in equation 2.3. It reflects the real material removal rate and improves the accuracy of dwelling time which helps realize controllable compensatory polishing.

2.3. Optimal design of motion axes of optical manufacturing system

In MRF, the tangential location error of the removal function can change the peak position of surface error, while the location error in normal direction can affect the stability of removal function [17]. The error caused by tangential location error can be modeled as [3]:

$$e(x,y) = \mathrm{grad}(r) * \Delta^{\mathrm{T}} \quad (2.4)$$

which means the surface error caused by tangential error is equal to the inner product of surface gradient and tangential error itself.

The location error changes the penetration depth of the removal function, which alters the stability of removal function. Its influence is modeled by experiment [7].

The optical manufacturing is realized by controlling the dwelling time on every dwelling point by changing the motion speeds, as shown in Figure 3. The system must decelerate or accelerate to demanded velocity to satisfy the speed change among different dwelling points; By taking the axes motion performance into account, the dwelling time is re-calculated; the relation between machine overall dynamic performance and optical surface accuracy is investigated.

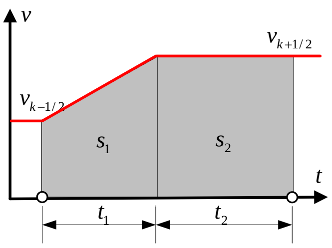

Figure 3. Schematic of the de/ac-celeration between dwelling points

In addition, based on the kinematics of multi-body system, the zero-order, first-order and second-order kinematic equation of the system are analyzed, so the geometrical accuracy, velocity and acceleration of the motion axes are obtained and improved to meet the demands from optical manufacturing.

Figure 4. Self-developed MRF and IBF machines

Based on above-mentioned research, we have developed series of MRF and IBF machines as shown in Figure 4. They successfully machined various optics including ultra-precision optics, space optics and laser optics.

3. Concluding remarks

Modern optical system puts higher standard on optics in terms of nanometer accuracy, high scale accuracy ratio, low surface damage and complex form, which presents more challenge to optical manufacturing. CCTOM, namely MRF and IBF, proves an effective manufacturing technique to confront these challenges. Future development will continue to focus on the issues of improving machining efficiency, measurement of complex form surfaces and zero-defect optical manufacturing, in order to meets the ever-evolving requirements from modern optical system.

5. Acknowledgements

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