euspen's 22nd International Conference & Exhibition, Geneva, CH, May/June 2022
www.euspen.eu

Research on CNC polishing technology of rotational symmetric aspheric optical elements

Zhengkai Wu[1] , Longfei Zhang[1] , Cheng Xue[1] , Jun Zha[1,2] , Yaolong Chen[1]

[1]*State Key Laboratory for Manufacturing Systems Engineering, Xi'an Jiaotong University, No.99, Yanxiang Road, Xi'an, Shaanxi,710054, China*
[2]*Xi'an Jiaotong University Suzhou Academy, 99 Ren-ai Road, Suzhou, Jiangsu, China, 215123*

zlf3616@stu.xjtu.edu.cn

Abstract
Aspheric optical elements have been widely used in vision systems. They are made traditionally by grinding and polishing on CNC machines. The final shape is achieved by polishing with different correcting strategies. The efficiency and repeatability of the polishing process is not high enough yet. This paper proposes a method based on a CNC controlled machine for the polishing of rotationally symmetric aspheric optical elements. A ring-shaped elastic polishing tool is used in the polishing process. The position and axis angle of the polishing tool are calculated according to the Preston's equation and an error compensation algorithm. The angle between the axis of the polishing tool and the normal of the workpiece surface will kept constant. The contact area between the polishing tool and the workpiece will be controlled to be approximately the same over the whole surface. The rotational speed of the workpiece and the feed speed of the polishing tool are precisely controlled to realize the uniform removal of the workpiece material during pre-polishing. In the finish polishing, the surface form error data measured by the profiler are used to calculate the feed speed and the pressure for form error compensation. In this way, the closed-loop compensation of the form error could be realized. The experiment results show that the form error PV 0.40 µm, RMS 0.11 um and the surface roughness Ra 4 nm could be achieved with a test work piece made of H-K9L optical glass.

keywords: aspheric, polishing , error compensation , form error

1. Introduction

With the development of optical technology, optical aspherical mirrors have unique advantages in optical components, and have been used more and more widely in the field of vision systems, such as lithography projection lenses, digital camera lenses and so on.

For the ultra-precision polishing technology of aspheric surface, there are several common processing technologies, such as magnetorheological processing, airbag polishing, ion beam polishing and so on[1]. Among them, the airbag polishing technology was jointly put forward by the London Optical Laboratory and the British Zeeko Company in 2000[2], which uses spherical airbags filled with low-pressure gas instead of small-diameter grinding discs for polishing. The polishing process is a precession process, that , while the airbag rotates, it also wobbles in different positions to obtain the Gaussian shape removal function.

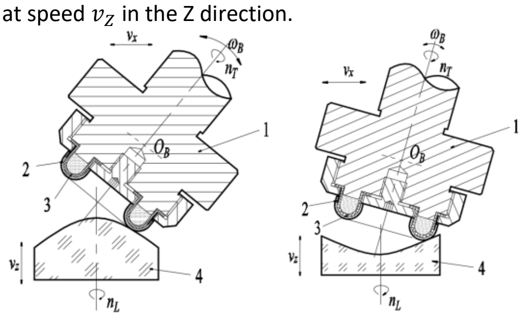
The machining error compensation technology is mainly divided into two kinds, one is the compensation based on the modification of the machining program, the other is the compensation based on the controller. Okafor[3] obtains the corresponding absolute coordinate error by measuring the relative coordinates of the machine tool space, and the error compensation processing is carried out by interpolation, and the final accuracy is improved by 2-4 times. By establishing a lathe error model including spindle offset, Donmez[4] inputs the error signal obtained by the laser measuring instrument into the controller through the Icano module, and realizes the real-time error compensation function.

Based on the actual production and processing process, this paper studies the polishing process and error compensation technology of aspherical optical components, and realizes the automation, digitization and high efficiency of the processing of rotationally symmetric aspherical components.

2. Aspheric polishing and compensation principle

2.1 Principle of point contact polishing process

Figure 1 shows a schematic diagram of polishing convex and concave aspheric surfaces. The polishing head is installed on the tool shaft, which can rotate around the axis of the tool shaft at a speed n_T, swing around the center point O_B of the B-axis at an angular velocity ω_B, and feed at a speed v_X in the X direction, the workpiece to be processed is installed on the workpiece shaft, It can be rotated about the spindle axis at speed n_L and fed at speed v_Z in the Z direction.



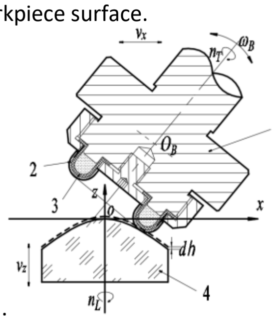
(a) Convex element polishing (b) Concave element polishing
1-elastic polishing head; 2-polyurethane polishing film; 3-rubber mold; 4-workpiece
Figure 1 Schematic diagram of the principle of aspheric point contact polishing

In theory, the contact between the polishing head and the workpiece is a point contact. In the process of aspheric polishing, the annular elastic polishing head is used for polishing.

The angle between the axis of the polishing head and the normal of the workpiece surface remains constant, and the area of each contact point between the polishing head and the workpiece is approximately the same.

2.2 Equivalent removal model of aspheric polishing materials

Figure 2 shows a schematic diagram of trajectory shaping polishing of convex aspheric surface with annular elastic polishing head. Point P is any point on the workpiece surface, the coordinate system xoz is the workpiece coordinate system, and the origin of the coordinate system coincides with the vertex of the workpiece surface.



1-elastic polishing head; 2-polyurethane polishing film; 3-rubber mold; 4-workpiece

Figure 2 Schematic diagram of polishing of rotational symmetrical aspheric surface

From the perspective of differential calculus, the processing volume dV of the polishing head on the workpiece surface can be approximated as the volume of a cylinder with a length of $2\pi x n(x)$, a width of dh and a height of dx per unit time, that is:

$$dV = 2\pi x n(x) dh dx \quad (1)$$

In the formula: dh is the amount of single removals during polishing.

Considering two points $P_1(x_1, y_1)$ and $P_2(x_2, y_2)$ at different positions, to ensure that the volume of material removed per unit time at the two points is the same, it is necessary to satisfy:

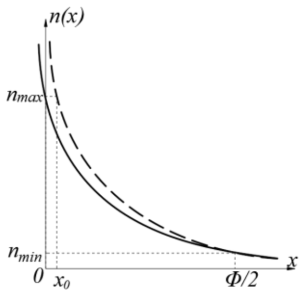
$$2\pi x_1 n(x_1) dh dx = 2\pi x_2 n(x_2) dh dx \quad (2)$$

The above expression is equivalent to:

$$xn(x) = C \quad (3)$$

In formula (3): C is a constant.

From this, the relationship between the workpiece speed n(x) and the machining position x in Figure 3 can be obtained. When the machining position is $x \to 0$, the workpiece speed is $n \to \infty$, which cannot be realized in actual machining. Therefore, the speed at x_0 is taken as the speed of the workpiece at $x = 0$. The maximum speed, that is, the theoretical speed curve is shifted to the left by x_0 distance. The solid line is the actual speed curve of the workpiece, and the dotted line is the theoretical speed curve of the workpiece.



Abscissa: machining position x, unit: mm;
Ordinate: workpiece speed n(x), unit: r/min

Figure 3 Diagram of the relationship between workpiece speed and machining position

Then the actual speed curve satisfies the equation:

$$(x + x_0)n(x + x_0) = C \quad (4)$$

Assuming that the maximum speed of the workpiece is n_{max} and the minimum speed of the workpiece is n_{min}, the analysis curve can be obtained:

$$x_0 n_{max} = x_{\emptyset/2} n_{min=C}$$
$$x_{\emptyset/2} - x_0 = \emptyset/2 \quad (5)$$

In the formula: $\emptyset$ is the clear aperture of the rotationally symmetric aspheric surface.

The solution is as follows:

$$x_0 = \frac{\emptyset n_{min}}{2(n_{max} - n_{min})} \quad (6)$$

Combining equations (4), (5), and (6), we can get:

$$n(x) = n(x + x_0) = \frac{\emptyset \cdot n_{max} \cdot n_{min}}{\emptyset n_{min} + 2x(n_{max} - n_{min})} \quad (7)$$

In CNC polishing, the polishing head moves horizontally in the X direction. Assuming that the feed rate of the polishing wheel in the X direction is $F(x)$, and the workpiece rotates once, the polishing wheel advances Δx in the X direction, then the relationship between $F(x)$ and workpiece speed $n(x)$ is shown in formula (8):

$$F(x) = n(x) \cdot \Delta x \quad (8)$$

In the formula: Δx is the processing step.

It can be seen from the formula (8) that the feed speed of the polishing wheel in the X direction is proportional to the rotational speed of the workpiece during machining. The feed speed of each processing point on the workpiece surface can be obtained by combining formulas (7) and (8):

$$F(x) = \frac{\emptyset \cdot n_{max} \cdot n_{min} \cdot \Delta x}{\emptyset n_{min} + 2x(n_{max} - n_{min})} \quad (9)$$

2.3 Preston hypothesis

In 1927, Preston[5] put forward the famous Preston hypothesis. He thought that to a large extent, the material removal rate in optical polishing process can be described as a linear equation :

$$\frac{dz}{dt} = KV(x, y, t)P(x, y, t) \quad (10)$$

In the formula: dz/dt —Material removal per unit time of polishing； K—Preston constant, which is related to various factors such as polishing die material, workpiece material, polishing fluid and so on； V(x,y,t)—Instantaneous relative velocity of polishing at a certain point of the workpiece； P(x,y,t)—Instantaneous polishing pressure at a certain point of the workpiece。

According to the Preston hypothesis, under the condition that the relative speed and pressure between the machined position and the machining tool are known, the material removal amount $\Delta z(x, y)$ of the machined position within the processing time t can be calculated:

$$\Delta z(x, y) = z_0(x, y) - z(x, y) = K \int_0^t V(x, y, t)\, P(x, y, t) dt \quad (11)$$

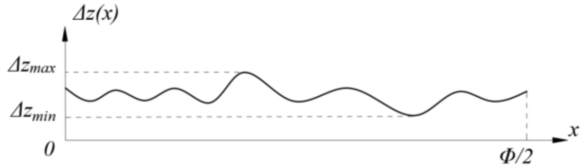
In the formula: $z_0(x, y)$—Workpiece surface height at time t=0； $z(x, y)$—Height of workpiece surface at time t.

It can be obtained from equation (11) that the amount of material removal at each point can be determined by controlling the relative velocity, pressure and polishing residence time at each point.

2.4 Error compensation algorithm for aspheric polishing

In the actual polishing process, because of the random error and systematic error, the material removal of each point on the workpiece can not be guaranteed by the variable speed and feed speed polishing method, and there will be a certain surface shape error in the actual measurement. Therefore, it is very important to study the error compensation algorithm in the process of aspheric polishing. According to the principle of Preston equation and the actual machining situation, the compensation scheme based on NC code modification is mainly adopted. At present, two ideas are proposed to compensate the error in the process of rotary symmetric aspheric polishing.

In the polishing process, due to the existence of different points of material removal is not completely consistent, such as Figure 4. Therefore, the feed speed of the polishing head at each point on the workpiece is modified by the feed speed compensation factor, so as to achieve the same amount of material removal at each point.



Abscissa: workpiece coordinate position x, unit: mm;
Ordinate: workpiece surface error Delta z(x)(difference between theoretical curve and actual curve), unit: um

Figure 4 Schematic diagram of aspheric polishing error

The expression of the compensation factor is:

$$\mathrm{k(x)} = \mathrm{a} + \mathrm{b}[1 - \frac{\Delta z(x) - \Delta z_{min}}{\Delta z_{max} - \Delta z_{min}}] \quad (12)$$

Where:

$\Delta z(x)$—The error value of the surface shape measured by the profiler after the best fitting of each point of the workpiece;

Δz_{max}—The surface shape error at the highest point of the error curve is generally positive;

Δz_{min} —The surface shape error at the lowest point of the error curve is generally negative;

a, b—Adjustment coefficient.

Therefore, the calculation method of feed speed after compensation is:

$$F'(x) = k(x) \cdot F(x) \quad (13)$$

For aspheric surfaces with large aspheric degree, there will also be less removal of edge materials during polishing. The experimental results show that the correction effect by feed speed is not ideal. In view of this situation, an approximate linear correction scheme for the compression amount of the polishing head at the edge of the workpiece is proposed. The correction algorithm is as follows:

$$\Delta Z = \mathrm{c} + \frac{d-c}{x_2 - x_1}(x - x_1) \quad (14)$$

Where:

x_1, x_2 is for the start and end coordinates of the area to be corrected;

c, d is the amount of compression to be set at the start and end of the area to be corrected;

Therefore, the calculation method of Z coordinate after compensation is:

$$Z = Z_0 + \Delta Z \quad (15)$$

Where: Z_0- Initial Z coordinate value.

3. Polishing and Compensation Experiment

The workpiece processed in this experiment is a rotationally symmetrical aspheric optical element with hairy embryo diameter 15 mm. The maximum asphericity of the aspheric surface is 0.73. It is a small and steep aspheric surface, so it is difficult to process.

The polishing equipment adopts the LPS200 optical CNC polishing machine developed by ourselves, and its appearance is rendered as shown in Figure 5. The polishing equipment is a X, Z, B three-axis CNC machine tool, which adopts a full closed-loop CNC system. The key functional components of the polishing machine are: tool axis system, workpiece axis system, precision pendulum head with resolution 1 arcsec, high-speed motorized spindle with rotational speed 12000 r/min, PA9000 CNC operating system and constant temperature polishing fluid circulation filtration supply system.

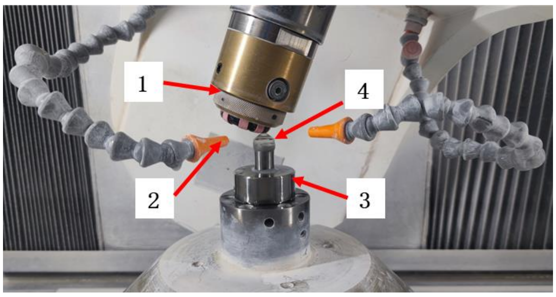
Figure 5 LPS200 Optical NC polishing Machine tool

In the aspect of polishing tools, a self-designed annular elastic polishing head is used to ensure the pressure of the polishing head by adding oil to the sealing oil plug. Compared with rigid polishing, its advantage lies in the flexible contact between the polishing head and the workpiece surface. The adaptive ability of the polishing head on the curved surface with great curvature change is improved, and the contact pressure between the polishing head and the workpiece is basically constant. And the surface of the workpiece will not leave machining marks after polishing, and its appearance is as shown by Figure 6.

1- Polyurethane polishing film; 2- Seal oil plug; 3- Pressure regulating oil plug

Figure 6 Physical drawing of elastic polishing head

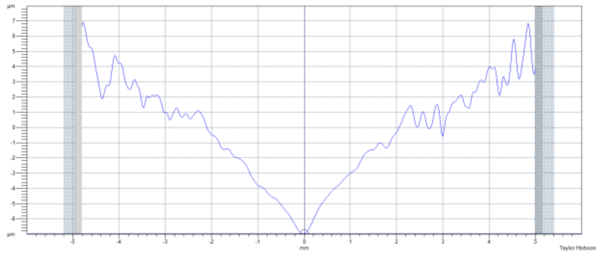
In the aspect of machining software, combined with the previous research on polishing compensation algorithm and actual machining verification, a CAM software based on aspheric polishing is designed and developed. The main function of the CAM software is to realize the machining trajectory planning and compensation machining function in the machining process of aspheric components. After inputting the relevant parameters of polishing head and aspheric surface in the software, the machining program for the first polishing can be generated, and the actual polishing site is shown in Figure 7.



1- Elastic polishing head; 2- Polishing liquid outlet pipe; 3- Bonding tooling; 4- Polishing workpiece

Figure 7 Field drawing of polishing process

After the first polishing, the British Talyor-Hobson profiler is used to detect the surface shape error of the workpiece. Figure 8 shows the detection curve when the filter length of the first polishing is 0.2.



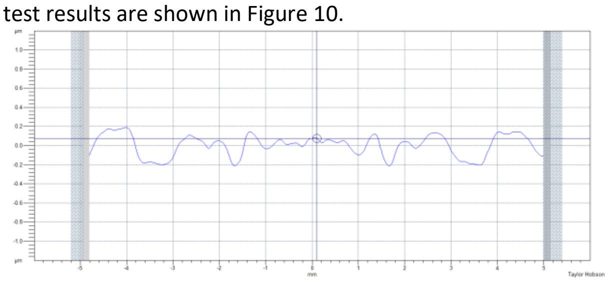
Abscissa: workpiece coordinate position x, unit: mm;
Ordinate: workpiece surface error Delta z(x) (difference between theoretical curve and actual curve), unit: um
Figure 8 Error curve after first polishing

As can be seen from the figure, the PV value of the surface shape error is about 13.895 μm, the middle part of the curve is low and the edge part is high, and the feed speed compensation and polishing pressure compensation are carried out on the curve at the same time. The left picture in Figure 9 shows the NC code before partial compensation, and the right picture shows the NC code after the corresponding part compensation.

(a) Before compensation	(b) After compensation
N3860 X0.0753 Z-0.1915 B15.746 S754 F7.54	N3860 X0.0753 Z-0.4855 B15.746 S754 F119.64
N3865 X0.06 Z-0.1531 B15.5968 S793 F7.93	N3865 X0.06 Z-0.4483 B15.5968 S793 F126.12
N3870 X0.0449 Z-0.1146 B15.4476 S836 F8.36	N3870 X0.0449 Z-0.411 B15.4476 S836 F133.27
N3875 X0.0298 Z-0.0761 B15.2984 S884 F8.84	N3875 X0.0298 Z-0.3737 B15.2984 S884 F141.2
N3880 X0.0149 Z-0.0376 B15.1492 S939 F9.39	N3880 X0.0149 Z-0.3364 B15.1492 S939 F150.04
N3885 X0 Z0.001 B15 S1000 F10	N3885 X0 Z-0.299 B15 S1000 F159.99

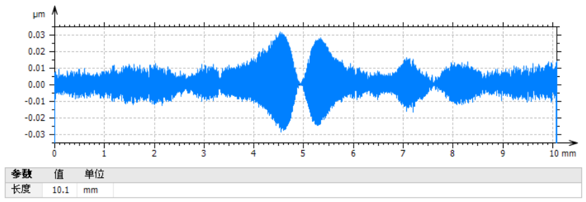
Figure 9 Pre-compensation and post-compensation NC codes

After several rounds of compensation processing, the final test results are shown in Figure 10.



Abscissa: workpiece coordinate position x, unit: mm;
Ordinate: workpiece surface error Delta z(x) (difference between theoretical curve and actual curve), unit: um
Figure 10 Final error curve

It can be seen that the PV value of the surface shape error converges to 0.40 μm, and the root mean square value of the surface shape error RMS converges to 0.11 μm, which achieves a higher machining accuracy. The surface roughness of the polished workpiece is detected by a profiler, and the test result is as shown by Figure 11.



Abscissa: workpiece coordinate position x, unit: mm;
Ordinate: surface roughness value , unit: um
Figure 11 Inspection diagram of workpiece surface roughness

It can be seen that the overall surface roughness Ra of the polished workpiece is 4 nm, which meets the requirements of finish.

4. Conclusions

The above results show that the polishing motion mode of variable speed and variable feed speed and the compensation scheme based on feed speed and polishing pressure are feasible, and higher machining accuracy can be achieved. What needs to be further studied are: 1) optimize the error compensation algorithm to accelerate the error convergence speed and further improve the polishing efficiency; 2) study and optimize the shape of the material removal function during polishing to find a more suitable residence time algorithm.

Acknowledgements

This work was supported by the Natural Science Foundation of Suzhou City SYG202018 & SYG202134.

References

[1] Yuan J, Zhang F and Dai Y 2010 Development research of science and technologies in ultra-precision machining field *Chinese Journal of Mechanical Engineering*. **46** 161-177
[2] Walker DD, Brooks D and King A 2003 The 'Precessions' tooling for polishing and figuring flat, spherical and aspheric surfaces *Optics Express*. **11** 958-964
[3] Okafor AC and Ertekin YM 2000 Vertical machining center accuracy characterization using laser interferometer - Part 1. Linear positional errors *Journal of Materials Processing Technology*. **105** 394-406
[4] Donmez MA, Blomquist DS and Hocken RJ 1986 A general methodology for machine-tool accuracy enhancement by error compensation *Precision Engineering-Journal of The American Society for Precision Engineering*. **8** 187-196
[5] Jones RA 1976 Optimization of computer-controlled polishing *Journal of the Optical Society of America*. **66** 1134