Control Method for the Tool Path in Aspherical Surface Grinding and Polishing

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KEYWORDS : Aspherical Lens, Grinding Tool Path, Surface Polishing, Nonlinear Curve Interpolation, PC-Based System

This paper proposes a control algorithm, which is verified experimentally, for aspherical surface grinding and polishing. The algorithm provides simultaneous control of the position and interpolation of an aspheric curve. The nonlinear formula for the tool position was derived from the aspheric equation and the shape of the tool. The function was partitioned at specific intervals and the control parameters were calculated at each control section. The position, acceleration, and velocity at each interval were updated during the process. A position error feedback was introduced using a rotary encoder. The feedback algorithm corrected the position error by increasing or decreasing the feed speed. In the experimental verification, a two-axis machine was controlled to track an aspherical surface using the proposed algorithm. The effects of the control and process parameters were monitored. The results demonstrated that the maximum tracking error with tuned parameters was at the submicron level for concave and convex surfaces.

Manuscript received: March 15, 2006 / Accepted: March 22, 2006

NOMENCLATURE

A_i = the magnitude of higher deviation from sphericity
a_i = acceleration of the vertical axis at the ith step (mm/s^2)
D = tool diameter (mm)
d_i = displacement of the vertical axis at the ith step (mm)
E = position error (mm)
f = equation of asphericity
h = control step size/interval (sec)
K_v = feedback gain
R = aspherical radius of curvature (mm)
r = acceleration rate constant
v_i = velocity of the vertical axis at the ith step (mm/s)
x = horizontal position of the aspherical surface (mm)
x_t = horizontal position of the grinding tool (mm)
z = vertical position of the aspherical surface (mm)
z_t = vertical position of the grinding tool (mm)
Δx, Δz = distances between the grinding tool center and the contact point (mm)
κ = conic constant
θ = contact angle (rad)

1. Introduction

Optical aberrations in aspherical lenses are slight compared to those in spherical lens. Aspherical lenses perform better per unit size than spherical ones and are useful for reducing the weight of optical products. The lenses are used for military devices and consumer electronics, such as digital cameras, DVDs, and cell phones. Since they are being used in many areas, the demand for these lenses has been gradually increasing. But the manufacturing requirements are intricate and productivity is low because the shape contains nonlinearities and ultrahigh accuracy during production is required.

Typical interpolation algorithms are derived from differentiating a curve. Aspherical curves, however, are nonlinear functions so it is hard to obtain an appropriate algorithm using conventional methods. It is also difficult to calculate the velocity required to track the curve.

Lee[1] developed a program for aspherical processing. The tool path was generated from the aspheric constants, material type, and shape of the surface. The path was calculated by a NC code, and the curves were interpolated on a NC-based machine after downloading the code to the machine. The concept of position control was discussed in the research, but a method for velocity control was not considered. Chen et al.[2] developed an ultraprecision grinding system in which the position error was predicted by geometric relationships and then added to the tool path. The concept, however, was based on position control, and a method for determining the velocity and acceleration was not discussed.

Some studies have examined interpolation algorithms used in the field of aspherical mirrors. Kim et al.[3] studied a compensation method for the deformation between a tool and the surface in which the deformation originated from the cutting force during turning. They installed sensors on the tool and the mirror, and measured the deformation, which was monitored on a PC in real-time, and then compensated for the error. Tsunemoto et al.[4] described a manufacturing method for a ceramic mirror using a diamond wheel. In their study, the tool angle was assumed to be fixed. The user inputs

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were the aspheric equation and the tool path, which were converted to NC commands. The control commands were downloaded through serial communications, so the control technique was not PC-based.

Cheng et al.[5] proposed a method to determine the amount of grinding required in which the surface accuracy afterwards was at the submicron level. Lei et al.[6] presented a method for aspherical grinding using ER fluid. Since the viscosity of the fluid changes in electronic fields, they mixed polishing chemicals in the ER fluid and controlled the process with electrodes. Lee et al.[7] succeeded in forming continuous surfaces with an eximer laser. Even though the shape they obtained was not from the equation of asphericity, a 500-μm spherical or parabolic surface could be produced with surface roughness R_a of 2–10 nm.

Yang and Hong[8] proposed a control algorithm for the simultaneous movement of three axes. The axes of a machine have a finite resolution, but curves are continuous; the difference between the two gives the control error. Their study showed how to discretize the surface function to minimize the position error.

Conventional studies for aspherical process have been limited to linearization and error compensation and discussions of the results because of the complexity of the equations and assumptions of NC-based systems. The interpolation algorithms have been developed using the performance of a NC controller. However, this study proposes a method to generate and track a tool path on a PC-based system when grinding or polishing aspherical lenses. The path is derived from the equation of asphericity, and is divided into intervals over which the ideal motion profiles are calculated. The motion profile is corrected during processing using the position error. The method is verified by applying the control algorithm to a three-axis machine and monitoring the response variation of the control parameters. Once the control parameters are tuned, the interpolation accuracy is tested.

2. Tool Path for Aspherical Lenses

2.1 Aspherical Surface

In general, the equation of asphericity consists of the shape of the lens and the aberration correction, and has nonlinear terms. The equation is written as

$$z = \frac{x^2}{R\left\{1+\sqrt{1-\frac{(k+1)x^2}{R^2}}\right\}} + \sum_{i=1}^{20} A_i \,|\, x \,|^i \tag{1}$$

where z is the sag of the lens, x is the displacement from the center, and R, k, and A_i are aspheric constants. Fig. 1 shows the convex and concave surfaces described by the equation. These curves were introduced in the verification tests.

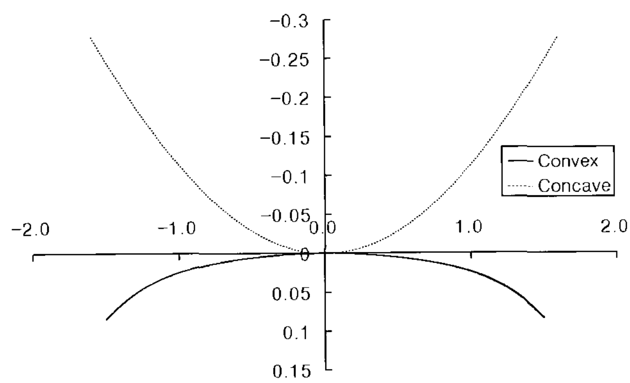

Fig. 1 Example of aspherical surfaces

2.2 Tool Path

It is difficult to interpolate an aspherical curve using conventional methods because of the nonlinearities arising from the square roots and absolute terms. The tool path can be obtained by differentiating the equation, although the procedure is complex.[9] If a spherical tool contacts an aspherical surface $z = f(x)$, as shown in Fig. 2, the contact angle θ can be written as

$$\tan\theta = z' = f'(x) \tag{2}$$

where z' is obtained from Equation (1). The end result, after several complex operations, is

$$z' = \frac{\frac{2x(1+g)}{R} - \frac{(k+1)x^3}{R^3}}{g(1+g)^2} + \sum_{i=1}^{20} \mathrm{sgn}(x) i A_i |x|^{i-1} \tag{3}$$

where g is defined to make the differentiation simpler, as follows:

$$g(x) = \sqrt{1-\frac{(k+1)x^2}{R^2}} \tag{4}$$

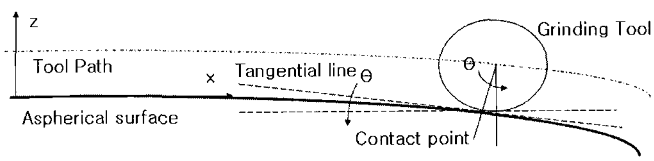

Fig. 2 Contact point and angle on an aspherical surface

The contact angle between a tool and an aspherical surface can be calculated from the differential equations. Common tools used for aspherical grinding or polishing have spherical shapes. If the contact angle is known, the distance between the center of the tool and contact point can be easily determined from geometric relations, as shown in Fig. 3.

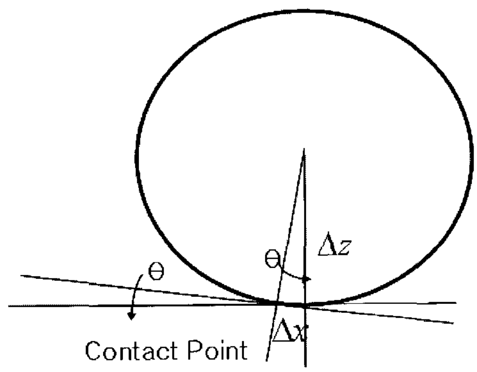

Fig. 3 Contact point and the center of a grinding tool

The position of a tool, *i.e.*, the center of a tool, can be written using the contact point and contact angle. The center is derived from the triangle shown in Fig. 3 using

$$x_t = x + \Delta x = x + \frac{D}{2}\sin\theta \tag{5}$$

$$z_t = z - \Delta z = z - \frac{D}{2}\cos\theta \tag{6}$$

3. Control Algorithm

Conventional methods for tracking aspherical surfaces are based on position control. The tool path is divided into sections, and the position is calculated at each interval. Then a machine moves to the coded positions. It is simple to generate NC codes using this method, but the intervals should be small to guarantee the continuity of the curve. Continuous variation of the velocity is also required to interpolate a curve. The control algorithm described in this section calculates the ideal motion profile and corrects the velocity using the position error. The concept of the algorithm is shown in Fig. 4. A curve is partitioned into intervals, and the profile at each section is updated. The motion profile consists of the position, velocity, and acceleration. The velocity and the acceleration are calculated from the ideal position, current position, and velocity at the previous step.

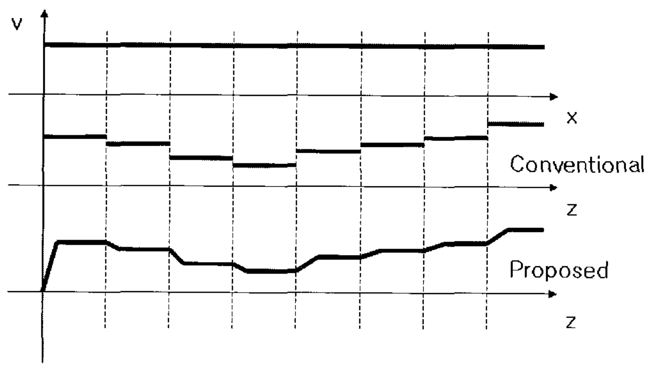

Fig. 4 Comparison of velocity profiles

Let h be the time interval, t_a the acceleration time, and r the acceleration ratio over a time interval. The acceleration time can then be written as

$$t_a = hr \tag{7}$$

Let the displacement take place in the z direction at step d_i, velocity v_i, and acceleration a_i. The displacement can be written as

$$d_i = \frac{1}{2} a_i t_a^2 + v_i (h - t_a) \tag{8}$$

The other way to calculate the displacement is from the position difference between steps on the aspherical curve,

$$d_i = f(x_{i+1}) - f(x_i) \tag{9}$$

The acceleration can be derived from Equations (7)–(9) and written as

$$a_i = 2\frac{f(x_{i+1}) - f(x_i) - v_i h(1-r)}{h^2 r^2} \tag{10}$$

The velocity after the acceleration is calculated from the acceleration time, amount of acceleration, and velocity at the previous step is

$$v_i = a_i hr + v_{i-1} \tag{11}$$

In an ideal situation, an arbitrary curve can be interpolated from the velocity and acceleration, which are calculated from design data. But the values must be corrected due to the position error that originates from mechanical fiction, vibration, and kinematical losses. The authors found that the velocity can be corrected by adding the position feedback terms to Equation (11):

$$v_i = a_i hr + v_{i-1} + K_v [f(x_i) - z] \tag{12}$$

This algorithm is useful for tracking an aspherical curve and submicron accuracy can be obtained in normal precision systems.[10] In this study, a function of the tool path is substituted and controlled instead of the aspherical surface, $f(x)$. The most important factor in an aspherical lens manufacturing machine is the position error, which is defined at the center of the tool. The current position is measured using a rotary encoder attached at the end of the axis from

$$E(z) = z_{encoder} - z_t(x) \tag{13}$$

4. Verification Experiment

4.1 Experimental System

The system used for the experiment had two axes: x and z. The x axis was transferred using a constant velocity after the process started. The velocity of the z axis was varied using a control signal in real time. The aspherical tool path was shaped by the relative motion of the x–z axes. Each axis was driven on a linear guide and ball screw. An air-guide system was installed on the x-axis to minimize the mechanical friction and to obtain a uniform velocity. The encoder provided the current position. The position error was used in a feedback loop to determine the velocity compensation. A photograph of the experimental apparatus is shown in Fig. 5.

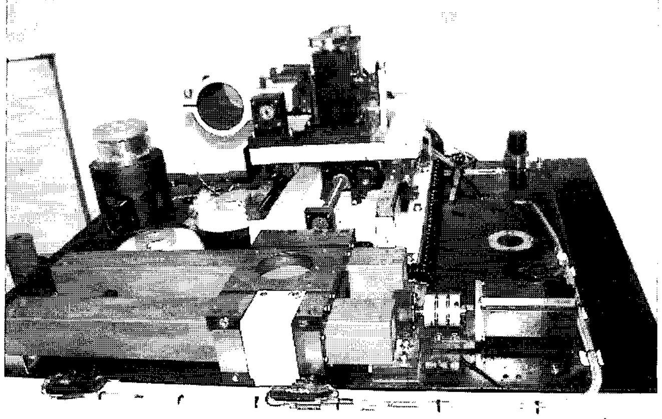

Fig. 5 Photograph of the experimental apparatus

The cutting force during the aspherical grinding process is very small because the tool and the lens are rotated by the air spindle. The feed rate in the experiment was much less than that used in common processes. The movement of the x-axis was unidirectional, while that of the z-axis was bidirectional. The speed variation was gradual so there was no shock or impulse during the processing. The ball screws and LM guides were accurate at a micron-precision level. The maximum stroke was within 5 mm for the x-axis and 2 mm for the z-axis. Therefore, the authors determined that the accuracy measured by the encoder was reliable, and the error between the encoder and the tool could be ignored.

A PCI-slot controller was installed in a PC. The generated code was sent to the motors without delay. The controller had an override function that could change the velocity or acceleration during movement. The operating program was developed with VC++ due to its user-friendly interface.

4.2 Procedure

The operating program was executed and the process parameters were entered. The parameters consisted of the aspheric constants, feed rate, tool diameter, and starting point. The program generated ideal values of the tool path, such as positions, velocity, and acceleration, using the given equations. The values were stored in the computer memory before the process started. During processing, the values were corrected by the position error and updated at each control position.

The convex and the concave surface models are shown in Fig. 1. The tool path for the models was generated, interpolated, and controlled. The position error during the tracking was measured to verify the algorithm.

After changing the size of intervals, acceleration ratio, feed rate, and control constant, the tool path tracking was tested to determine the effect of the parameters. After the parameters were tuned, the tendency of the diameter variation was monitored. The tool diameter was varied virtually from 1.0 to 5.0 mm, *i.e.*, the tool diameter was changed numerically in the equation. The tool path was modified by changing the tool diameter, and the control error variation was observed from the path change. The specification of the control system and lenses in the experiment are listed in Table 1.

Table 1 Experimental conditions

	Contents	Axis/Parameter	Value
Machine	Resolution	X	0.2 µm
		Z	0.1 µm
	Accuracy	X	1.0 µm
		z	0.1 µm
	Backlash	x	1.0 µm
		z	0 µm
Lens	Convex	Diameter	1.5 mm
		Height	84.05 µm
		R	22.405
		k	43.098
	Concave	Diameter	1.6 mm
		Height	279.19 µm
		R	-4.254
		k	-3.359

5. Results

5.1 Effect of the Control Parameters

Figs. 6 and 7 show the response variation when the control interval was changed from 0.002 to 0.1. The position error increased at the end of both sides on the convex and concave surfaces. When the interval decreased, the average of the error also decreased. But when the interval was too small, the number of data points increased rapidly and the controller could become overloaded. The controller had a minimum processing time; the size of interval should be determined based on this capacity of the controller.

Figs. 8 and 9 give the results of varying acceleration ratio from 0.1 to 0.9. The position error increased with the magnitude of the ratio, but the response variation was small, between 0.1 and 0.7. This parameter was related to the smoothness of the interpolation. Thus, the system response could become worse if the value were too small.

The x-axis was transferred using a constant speed. However, the z-axis was controlled and the velocity was varied after monitoring the movement of the x-axis. Thus, the response could be delayed. The productivity increased with the feed speed, but control performance grew worse. This tendency appeared for both surfaces, as shown in Figs. 10 and 11.

Figs. 12 and 13 show the response variation when the control constant for the velocity correction was changed from 0.5 to 4.0. The position error decreased as the constant increased. However, the control response will become unstable and jump sharply due to small disturbances if the value is set too high.

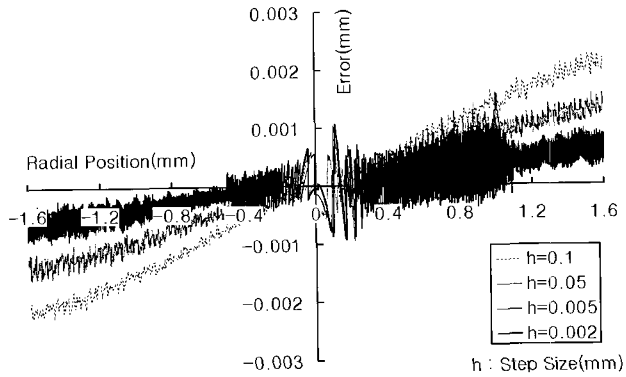

Fig. 6 Error variation with interval size for the convex surface

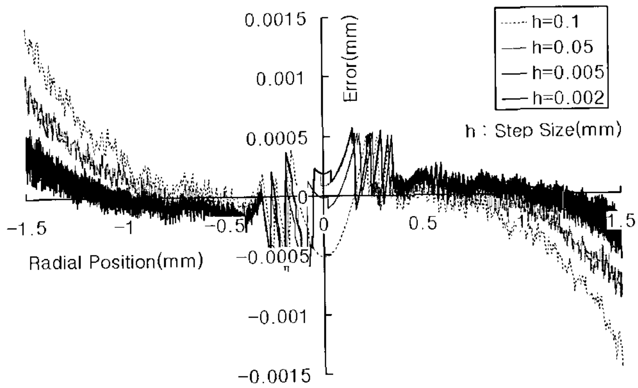

Fig. 7 Error variation with interval size for the concave surface

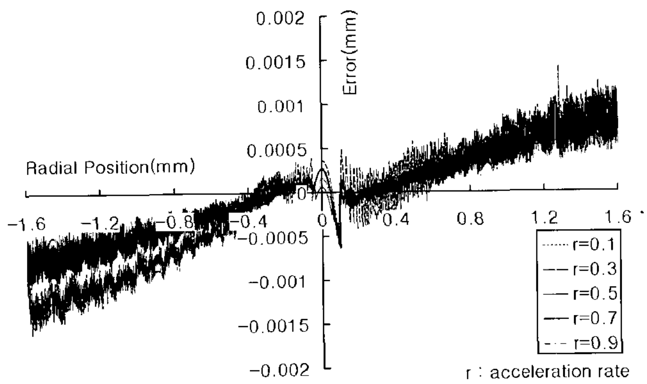

Fig. 8 Error variation with acceleration ratio for the convex surface

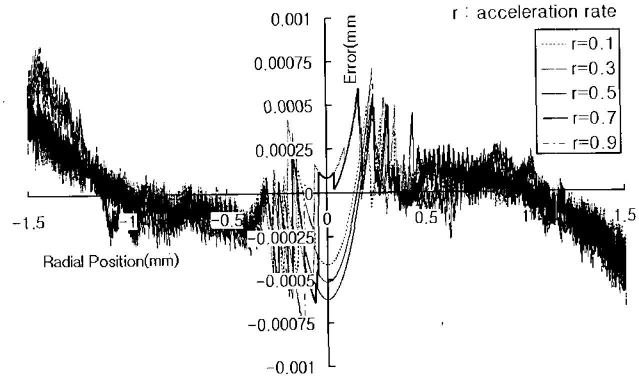

Fig. 9 Error variation with the acceleration ratio for the concave surface

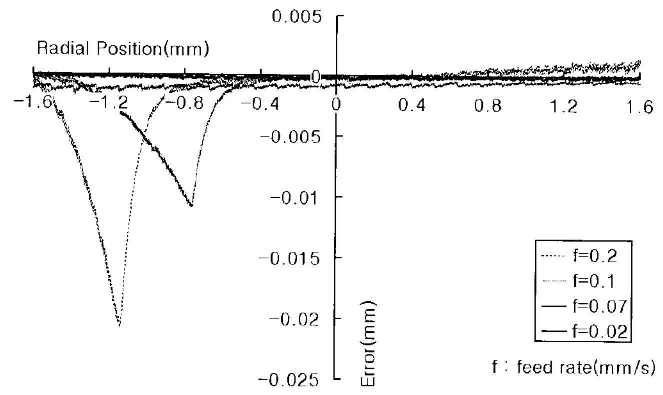

Fig. 10 Error variation with feed rate for the convex surface

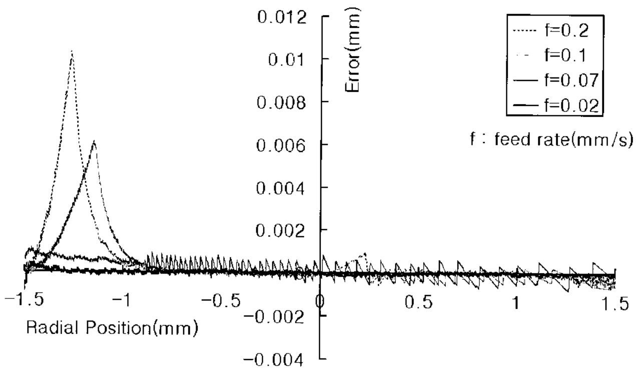

Fig. 11 Error variation with feed rate for the concave surface

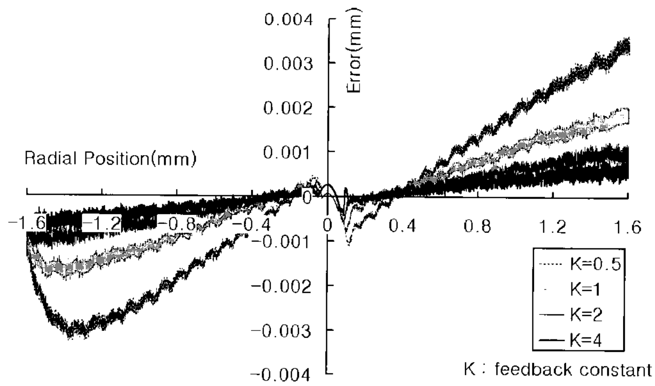

Fig. 12 Error variation with feedback constant for the convex surface

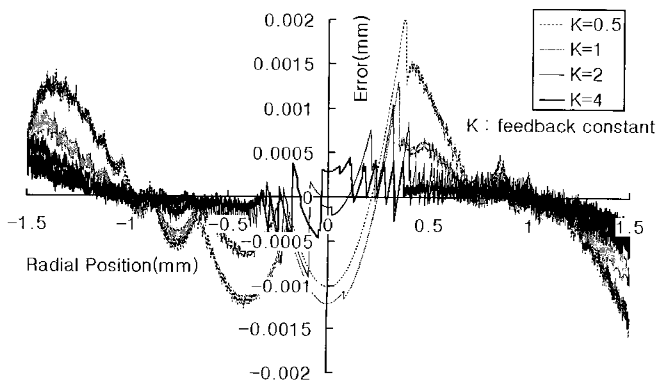

Fig. 13 Error variation with feedback constant for the concave surface

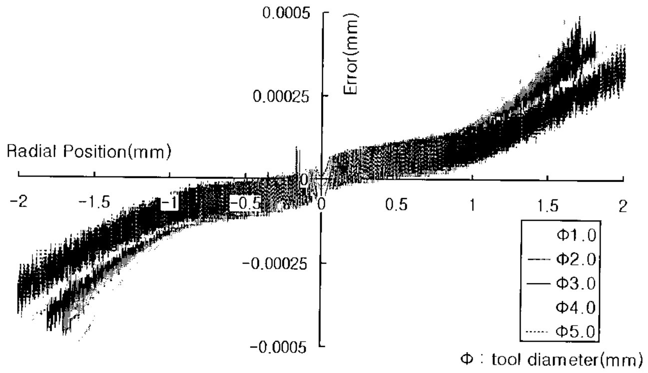

Fig. 14 Error variation of the tool path for the convex surface

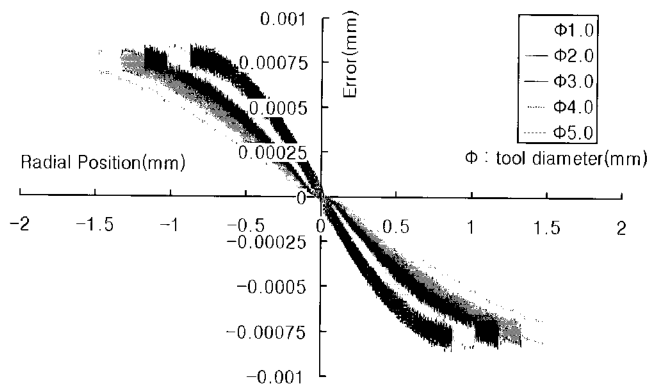

Fig. 15 Error variation of the tool path for the concave surface

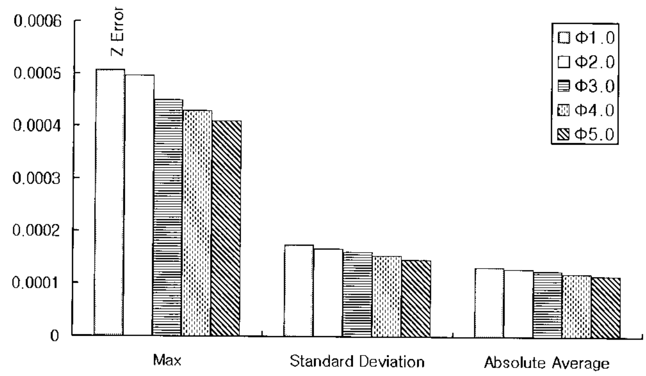

Fig. 16 Error variation with the tool diameter for the convex surface

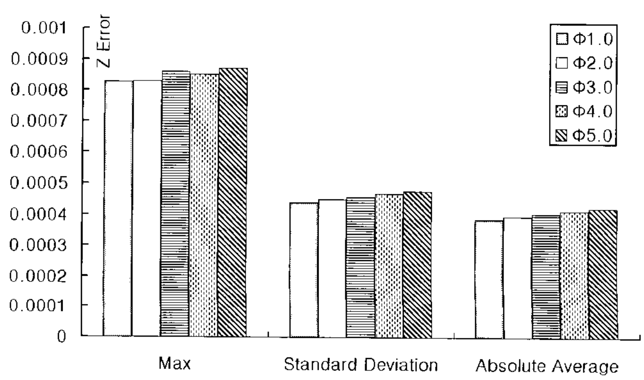

Fig. 17 Error variation with the tool diameter for the concave surface

5.2 Effect of the Tool Diameter

The parameters were tuned based on the results in the previous section. The virtual tool diameter was varied from 1.0 to 5.0 mm, and the tracking tests were performed using these parameters. The results are shown in Figs. 14 and 15. The maximum position error on the convex surface was 0.5 μm, and the average error was 0.1 μm. The accuracy increased with the diameter increments. The position error on the concave surface was within 1 μm, but the accuracy decreased with the tool diameter. The convex surface became fluent as the tool diameter increased, opposite to the concave surface.

Figs. 16 and 17 show the maximum, average, and standard deviation of control error obtained from interpolating the curves. The three values of the error decreased with the size of the tool diameter on the convex surface, but the tendency was reversed on the concave surface. Therefore, larger tools produced better convex surfaces and smaller tools produced better concave surfaces. The maximum error was less than 1 μm for both surfaces.

6. Conclusions

A tool path was generated for an aspherical surface from the derived equations. The generated path was interpolated using the proposed algorithm. An air-guide and precision components were installed in the test machine, and the response variation of the position error was monitored during interpolation. The control interval, acceleration ratio, feed rate, and feedback constant were varied.

The parameters were tuned and set to test the effect of the tool diameter variation. The maximum error was 0.5 μm for the convex surface and 1.0 μm for the concave surface. These results demonstrate that the proposed algorithm can be applied to the grinding and polishing processes used to manufacture aspherical lenses.

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