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Model-based self-optimization method for form correction in the computer controlled bonnet polishing of optical freeform surfaces

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Abstract: Freeform surfaces have become increasingly widespread in the optical systems for enhanced performance and compact lightweight packaging. The geometrical complexity and high precision requirements of optical freeform surfaces for various functional optical applications, has posed great challenges in the design, precision machining, and measurement of these surfaces. This paper presents a model-based self-optimization approach for precision machining and measurement of optical freeform surfaces in the computer controlled bonnet polishing (CCBP) process. To realize the technical feasibility, the process parameters and motion control are accurately performed through modelling and simulation of machining processes, error compensation, and on-machine metrology.

OCIS codes: (220.0220) Optical design and fabrication; (220.4610) Optical fabrication; (220.5450) Polishing.

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1. Introduction

Optical freeform surfaces have become increasingly widely used in the optical systems for enhancing the performance and making the system to be more compact, and light in weight [1]. Due to the geometrical complexity and high precision requirements of freeform surfaces for various functional optical applications, this has imposed great challenges in the design, precision machining and measurement of these surfaces [2]. Computer controlled bonnet polishing (CCBP) is an enabling technology that actively controls the position and orientation of a spinning, inflated the bonnet as it sweeps through the polished surfaces [3]. CCBP has the advantage of high polishing efficiency, mathematically tractable influence function, and flexibly controllable spot size with variable tool hardness [4]. As a result, CCBP is one of the promising ultra-precision polishing technologies which shows a great potential with regard to the application in the fabrication of freeform surfaces with sub-micrometer form accuracy and surface finish in nanometer level.

Previous research work in the field of CCBP has always focused on the development and application of precess polishing processes [5], edge control [6–8], as well as tool path and dwell time optimization [9, 10]. It is well known that the purpose of polishing is to correct form error of the surface [11] and reduce the roughness of the surface by iterative loops to meet the desired specifications [12]. Beaucamp et al. [13] firstly used full-factorial analysis to identify the process parameters which is capable of achieving surface roughness below 0.5 nm root-mean-square value (Rq) while maintaining relatively high removal rates, and then conducted corrective polishing experiments using influence functions generated on a workpiece of the same material and curvature. The problem is a lot of experiments are needed to be carried out for identifying the process parameters and acquiring the influence functions when corrective finishing of new materials or new surface designs. Since the optimal cutting conditions and polishing strategy for ensuring good surface quality depend largely on the machining environment, work materials and the geometry of surfaces being polished [14], there is a need for modeling and simulation methods and tools which can simulate and predict the effect of different factors and surface generation mechanisms, and the form correction process. Wu et al. [15] conducted the experimental and theoretical study on corrective polishing of flat surface and calculated the dwell time by using Guassian-shaped influence function. The deviation between presumptive and measured influence functions may lead to time-consuming form correction process and low convergence rate. It is also found that the corrective polishing of freeform surfaces by CCBP has received relatively little attention.

This is particularly true for ultra-precision, multi-axis, freeform polishing, which is a kind of non-conventional polishing method that has been used for machining ultra-precision freeform components that require precise control and accuracy across the polishing surface so as to maintain the form accuracy and achieve nanometric surface finish, which improve the functionality of the components.

As a result, this paper attempts to present an integrative study of a model-based self-optimization method for precision machining and measurement of freeform surfaces in the CCBP. As shown in Fig. 1, the self-optimization method employs a model-based simulation system to transfer expert knowledge together with on-machine measurement data and optimization simulations into dwell time algorithm for an increase in robustness and efficiency of corrective polishing of optical freeform surfaces with respect to the surface quality. Unlike the traditional form correction method widely used in computer controlled polishing processes, the proposed method allows to change the polishing tool influence function during the polishing process and then determines a dwell time-profile for corresponding polishing tool in order to minimize the surface error-profile. To realize the technical feasibility of the self-optimization approach, the process parameters and motion control are accurately performed through modelling and simulation of machining processes, error compensation, and on-machine metrology. A model-based simulation system is firstly developed for optimizing the polishing parameters and predicting the surface generation and residual error in the form correction process. Hence, an on-machine metrology system is presented which enables in situ measurement of freeform surfaces for supporting online compensation of machining errors. After that, an inverse model is built to determine the corresponding process parameters and dwell time on each track point along the polishing path so as to achieve the designed form accuracy. A series of simulation and polishing experiments have been conducted on a sinusoidal and a progress surfaces so as to verify the capability of the model-based self-optimization system. The results show that the proposed method can be successfully used for corrective polishing of freeform surfaces.

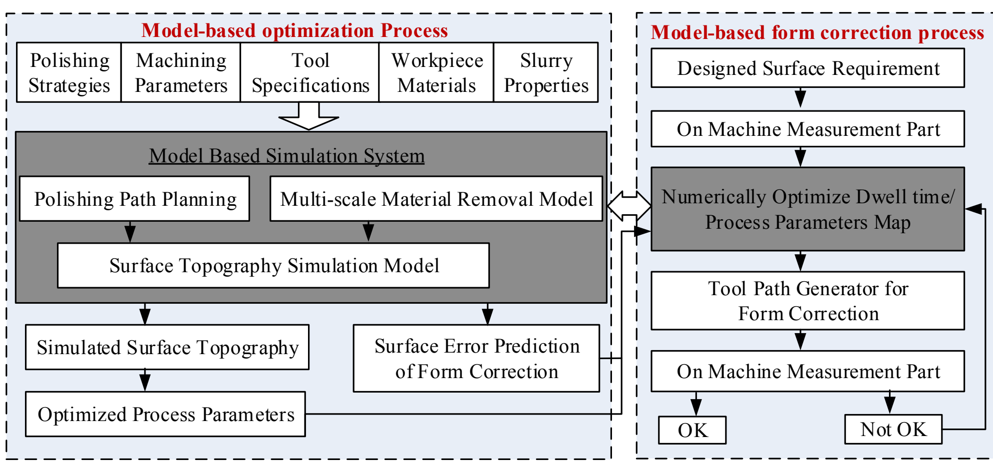

Fig. 1. Architecture of the model-based self-optimization system for form error compensation in computer controlled bonnet polishing.

2. Model-based simulation system

Model-based simulation system is the forward problem which predicts the surface profile of polished part produced by a convolution integral of the tool influence function and cross feed velocity. In this section, a multi-scale material removal model is presented based on the study of contact mechanics, kinematics theory and wear mechanisms. While the prediction of surface generation by CCBP is formulated in matrix form and expressed by summing the discrete material removal amount over equidistant track points along the polishing path.

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2.1 Multi-scale material removal model

A multi-scale material removal model, developed based on the prior work done by the authors [16], is used for predicting the influence function in CCBP. According to the schematic diagram in Fig. 1, the influence function $R(x, y)$ can be expressed as,

$$R(x,y)=\frac{2\eta K_{ac}V_c t}{H_w \tan\alpha}\left(\frac{R_a}{\sigma_z}\right)^{1/2}\cdot P(x,y,R_b,d,\omega,Y,\nu,\varphi,\eta_1,\eta_2)\cdot V(x,y,S,\varphi,R_b,d) \quad (1)$$

where η is the volume fraction of a wear groove removed as wear debris, K_{ac} is the coefficient related to the particle size distribution and the hydrodynamics condition, V_c is the volume fraction of the polishing slurry, t is the constant polishing time, H_w is the hardness of polished workpiece, α is the semi-angle of the cone particle, R_a is the radius of the pad asperities, σ_z is the standard deviation of asperity heights, $P(x,y,R_b,d,\omega,Y,\nu,\varphi,\eta_1,\eta_2)$ is the pressure distribution at the polishing contact area, and $V(x,y,S,\varphi,R_b,d)$ is the relative velocity distribution between the polishing pad and the target surface in the polishing area.

$$V(x,y,S,\varphi,R_b,d)=\frac{\pi S}{30}\sqrt{\left(x\cot\varphi-(R_b-d)\right)^2(\sin\varphi)^2+y^2(\cos\varphi)^2} \quad (2)$$

where $x^2+y^2\le(R_b)^2-(R_b-d)^2$; S is angular velocity in rpm; φ is the swing angle; d is the polishing depth in mm; R_b is the radius of the bonnet in mm.

$$P(x,y,R_b,d,\omega,Y,\nu,\varphi,\eta_1,\eta_2)=p_0\left(1-\frac{x^2}{a^2}-\frac{y^2}{a^2}\right)^{1/2}+\frac{(1-2\nu)(1+\nu)}{Y}\cdot\frac{\omega\cos\varphi(2\eta_2+\eta_1/3)p_0 y(R_b-d)}{a^2}\cdot\left(1-\frac{x^2}{a^2}-\frac{y^2}{a^2}\right)^{-1/2}+\frac{(1-\nu)^2}{Y}\cdot\frac{\omega\cos\varphi(2\eta_2+\eta_1/3)\pi p_0 y}{2a} \quad (3)$$

where $a=\sqrt{dR_b}$ denotes the radius of contact area, Y and ν are Young's modulus and the Poisson ratio, respectively, while η_1 and η_2 are the coefficients of viscosity related to shear and bulk deformation, respectively. ω is the angular velocity, and $p_0=3F_N/(2\pi a^2)$ denotes the maximum contact pressure, F_N is the total elastic force, acting on the surface (in normal direction) on the polishing pad:

$$F_N=\frac{2}{3}\frac{Y}{(1-\nu^2)}R_b^{1/2}d^{3/2} \quad (4)$$

2. 2 Surface generation model

It is well known that the surface generation of the polishing process can be regarded as the convolution of the influence function and the dwell time map along the pre-specified tool path. In the practical polishing process, the motion of polishing tool on the target surface is achieved by the discrete track points along the specified polishing path, and the polished surface is then characterized by the measured sample points. Previous study found that a relative and cumulative process is proven to be a key surface generation mechanism in bonnet polishing [17]. As a result, it is able to relate the discrete material removal amounts on the polished surface to the discrete process parameters in each track point along the polishing

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path by discretizing the polishing process. When the polishing tool scans all the track points on the target surface, the actual material removal amounts, $Z_a(x_k, y_k)$, on a given point can be described as

$$Z_a(x_k, y_k) = \sum_{i=1}^{N_t} R(x_k - \xi_i, y_k - \eta_i) D(\xi_i, \eta_i) \tag{5}$$

where N_t is the total numbers of track points. $R(x_k - \xi_i, y_k - \eta_i)$ is the material removal rate at point (x_k, y_k) when the center of the polishing tool dwell on the track point (ξ_i, η_i). $D(\xi_i, \eta_i)$ is the dwell time of the polishing tool at the track point (ξ_i, η_i) along the polishing paths, and can be expressed as

$$D(\xi_i, \eta_i) = T_f(\xi_i, \eta_i) + T_a(\xi_i, \eta_i) \tag{6}$$

$T_a(\xi_i, \eta_i)$ is the additional dwell time on the track point (ξ_i, η_i) for producing the designed surface profile, which can be determined by the dwell time algorithm; $T_f(\xi_i, \eta_i)$ is the associative dwell time which correlates with the surface feed rate of the polishing tool, and can be expressed as

$$T_f(\xi_i, \eta_i) = \frac{\Delta d(\xi_i, \eta_i)}{V_f(\xi_i, \eta_i)} \tag{7}$$

$\Delta d(\xi_i, \eta_i)$ is the distance of adjacent track points for the track point (ξ_i, η_i), and $V_f(\xi_i, \eta_i)$ is the surface feed rate of polishing tool on the track point. The produced surface map, $Z_p(x_k, y_k)$, can be found by subtracting the actual material removal height from the initial height map:

$$Z_p(x_k, y_k) = Z_m(x_k, y_k) - Z_a(x_k, y_k) \tag{8}$$

3. Principle of form correction process in CCBP

The form correction process is commonly achieved by determining process parameters on each track point along the polishing path, such as the tool feed rate or dwell time, based on measured data so as to achieve a desired surface profile. The implementation of form correction can be divided into two major parts. The first part involves online measurement of the target surface, which can be solved by the developed on-machine measurement system. With the availability of such information, the second part is the determination of the dwell time distribution corresponding to each track point along the calculated polishing tool path on target surface.

3.1 On-machine measurement system

Research into self-optimization process of form correction critically depends on the ability of on-machine measurement. There is no way of knowing how much material was removed and whether the desired surface shape and roughness are achieved if the target surface cannot be measured. The accuracy with which the surface can be measured limits the accuracy with which the polishing processing can be carried out. Due to the additional position error if the workpiece is taken off for traditional off-line measurement instruments and remounted on the machine tool, it is difficult to compensate the machining error for the precision machining of complex shaped optical freeform surfaces [18]. To address this problem, an on-machine measurement system attached to the motion axis of polishing tool has been designed and a prototype has been built to monitor the surface condition during the form correction process, as shown in Fig. 2. The system includes a Keyence LK-H022 laser displacement sensor, a

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Keyence LJ-G5000 controller, the optical motion sensor MCS-12085 and the micro-controller ATmega128A for detection of the motion of the polishing machine. The laser sensor has a high measurement repeatability of 0.02 μm. The laser sensor and the motion sensor are connected to the personal computer via the USB port. The laser sensor is mounted on the B axis of a Zeeko IRP200 7-axis polishing machine via a purposely-designed fixture, while the workpiece is mounted on the C axis. The laser displacement sensor is adjusted to be perpendicular to the X-Y plane. Linear motions of the X axis, Y axis and Z axis of polishing machine are used for the implementation of the designed sampling positions of the laser sensor module across the target surface. It should be noted that the distance between the laser scanner and the target surface is adjusted according to the measuring range of the laser sensor. The working distance of the Keyence sensor is set to be 20 mm, which is the suggested reference distance by the sensor specification so as to ensure the accuracy. The tool path for measurement is generated by MATLAB code and the CNC file for the scanning trajectory is implemented on the polishing machine. The scanning path and the sampling positions are shown in Fig. 3. During the scanning of the surfaces, the data of the motion sensor is monitored by the PC and once the workpiece is moved to the programmed position, the measured data from the laser sensor is acquired by the PC and recorded as a data file for subsequent processing.

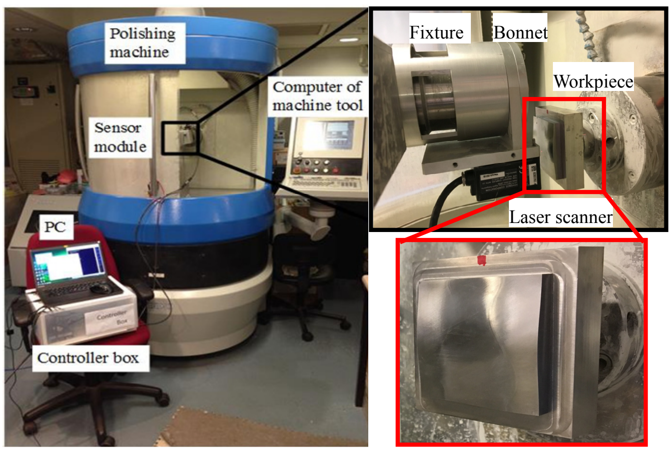

Fig. 2. Experimental setup of the on-machine measurement system.

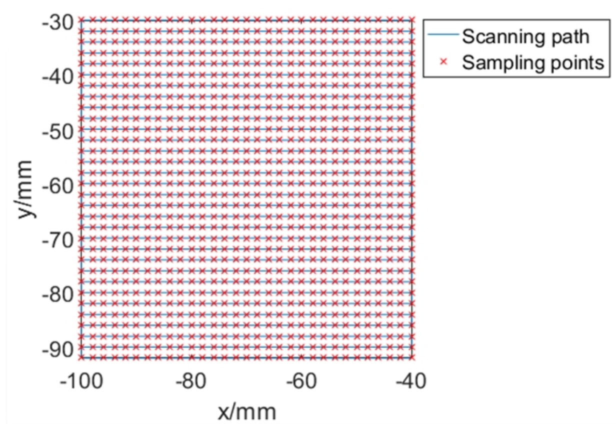

Fig. 3. Scanning path and sampling positions for the on-machine measurement.

The desired material removal distribution which is critical to improve the form accuracy can be found by subtracting the final desired surface profile from the measured surface height map:

$$Z_d(x_k, y_k) = \mathrm{Z}_m(x_k, y_k) - Z_f(x_k, y_k) \tag{9}$$

where $k = 1, 2 \ldots N_r$ and N_r denotes the total number of sample points of the surface error map. $\mathrm{Z}_m(x_k, y_k)$ and $Z_f(x_k, y_k)$ are the measured and desired final heights of sample point (x_k, y_k). Since misalignment exists between the coordinates of the measured surface and the designed surface, surface matching is required to eliminate the misalignment of the coordinate frame. In this study, the measured data has to be registered to the designed surface by a freeform surface characterization method which is purposely built based on an iterative closest point (ICP) method [19]. Hence, the measured surface is registered to the designed surface with the ICP method and the transformation matrix was obtained. Based on the calculated transformation matrix, the desired material removal distribution showing the deviation of the measured and the designed surface is determined by registering the measured results with the original designed surface.

3.2 Dwell time algorithm

For corrective polishing of freeform surfaces, the success of form error compensation depends on the accuracy of the control of surface removal in the normal direction of the work surface, which is commonly implemented by accurate control of the material removal rate and dwell time on each track point. Hence, the calculation of dwell time distribution of tool motion around the domain area of surface profile becomes a key to successfully perform the task of form error compensation. In the form error correction process, since the machining zone of polishing tool is finite contact area (mainly decided by the bonnet radius and the tool offset) rather a mathematical point, tack points within this contact area simultaneously sustain machining action. As a result, the total machining time of each track point is the accumulation of tool dwelling time whenever the tool is at a position with this point inside the machining zone [20].

To completely overcome the edge effect in the practical polishing process, the center of polishing tool should overhang the workpiece edge, with a minimal extended distance equal to the half-width of influence function employed along the polishing paths. Accordingly, the surface form map should be extended with a minimal distance equal to the full-width of influence function in numerical simulations. In this study, Gerchberg band-limited extrapolation method was used to avoid the edge saltation in dwell time calculation [21]. With the help of

$$Z_a(x_k, y_k) = Z_{ak}, \qquad Z_d(x_k, y_k) = \mathrm{Z}_{dk}, \qquad R(x_k - \xi_i, y_k - \eta_i) = R_{ki}$$
$$D(\xi_i, \eta_i) = D_i, \qquad T_f(\xi_i, \eta_i) = T_{fi}, \qquad T_a(\xi_i, \eta_i) = T_{ai},$$

Equation (5) can be expressed as

$$\begin{bmatrix} Z_{a1} \\ Z_{a2} \\ \vdots \\ Z_{aN_r} \end{bmatrix} = \begin{bmatrix} R_{11} & R_{12} & \cdots & R_{1N_t} \\ R_{21} & R_{22} & \cdots & R_{2N_t} \\ \vdots & \vdots & \vdots & \vdots \\ R_{N_r1} & R_{N_r1} & \cdots & R_{N_rN_t} \end{bmatrix} \begin{bmatrix} T_{f1} \\ T_{f2} \\ \vdots \\ T_{fN_t} \end{bmatrix} + \begin{bmatrix} R_{11} & R_{12} & \cdots & R_{1N_t} \\ R_{21} & R_{22} & \cdots & R_{2N_t} \\ \vdots & \vdots & \vdots & \vdots \\ R_{N_r1} & R_{N_r1} & \cdots & R_{N_rN_t} \end{bmatrix} \begin{bmatrix} T_{a1} \\ T_{a2} \\ \vdots \\ T_{aN_t} \end{bmatrix} \tag{10}$$

Through replacing the left term by the designed material removal distribution $Z_d(x_k, y_k)$, the deconvolution operation of dwell time would then become the solution of the matrix equation. Since matrix R tend to be a singular or approximately singular matrix with a large condition number, Eq. (10) is mostly an ill-conditioned problem and the possible negative dwell time solution cannot be applied for practical polishing process. To solve this problem, the Tikhonov regularization method is firstly used by introducing a damped factor λ as shown in Eq. (11) [15, 22]. Hence, a least square QR decomposition (LSQR) method is used to calculate the dwell time distribution that minimizes the 2-norm of residual error correlated with the extended surface error and the RMS of residual error correlated with the original surface error [23, 24]. Since changing the polishing tool removal characteristic during the polishing process is a promising approach to reduce the process time [25] and edge control [13], the matrix R with time-variant influence functions can be calculated by using the model-based simulation system as described in Section 2. After that, the dwell time is determined for all track points by inverse calculation using the measurement data of the error map and the corresponding influence function with the model-based simulation system.

$$\begin{bmatrix} Z_{a1} \\ Z_{a2} \\ \vdots \\ Z_{aN_r} \\ 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix} = \begin{bmatrix} R_{11} & R_{12} & \cdots & R_{1N_t} \\ R_{21} & R_{22} & \cdots & R_{2N_t} \\ \vdots & \vdots & \ddots & \vdots \\ R_{N_r1} & R_{N_r1} & \cdots & R_{N_rN_t} \\ \lambda & 0 & \cdots & 0 \\ 0 & \lambda & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \lambda \end{bmatrix} \begin{bmatrix} D_1 \\ D_2 \\ \vdots \\ D_{N_t} \end{bmatrix} \tag{11}$$

3.3 Tool path planning for optical freeform surfaces

To realize freeform polishing process, a tool path generator (TPG) has been purposely built which is used for generating the CNC files for corrective polishing as shown in Fig. 4. The path control of the corrective polishing process is quite different from that of other ultra-precision machining processes where the local removal is determined by the influence function and dwell time of the polishing tool. The track coordinates and surface normal vectors are calculated for ensuring optimized polishing gestures across the entire polished surface. The subsequent calculation of the control parameters for each motor of polishing machine is done through a specially created post processor covering the kinematic correlations of the entire machine tool. The G-code program for the polishing machine is laid out to guide the polishing module across the workpiece surface in order to achieve the form correction.

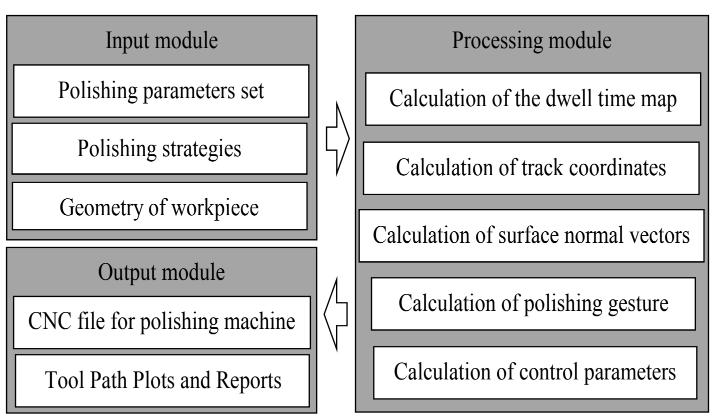

Fig. 4. Schematic diagram of tool path generator for freeform polishing.

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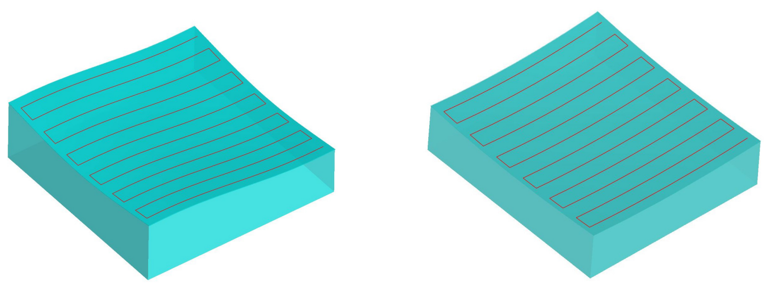
In this study, the sinusoidal and progressive lens surfaces are made of steel which are used to conduct the experoments for realizing the corrective polishing of the optical freeform surfaces. Figure 5 shows the freeform surfaces and the trajectory information of the polishing tool given into a G-code based program for the polishing machine. Figure 5(a) shows the designed sinusoidal surface which can be expressed by

$$Z = \sin(\frac{2\pi x}{60}) + \cos(\frac{2\pi y}{60}) \tag{12}$$

where $x \in [-30,30]$ and $y \in [-30,30]$. Figure 5(b) shows the designed progressive lens surface which can be expressed by

$$\begin{aligned} Z = {} & 0.462\times\sqrt{3}\times\left(2x^2+2y^2-1\right)-0.015\times2\sqrt{2}\times\left(3x^2y-y^3\right) \\ & -0.046\times2\sqrt{2}\times\left(3x^2y+3y^3-2y\right) \\ & +0.007\times2\sqrt{2}\times\left(3x^3+3xy^2-2x\right)+0.007\times2\sqrt{2}\times\left(x^3-3xy^2\right) \\ & +0.0064\times2\sqrt{3}\times\left(10x^4\mathrm{y}+20x^2y^3-12x^2y+10y^5-12y^3+3y\right) \end{aligned} \tag{13}$$



(a) Sinusoidal surface (b) Progressive lens surface

Fig. 5. Trajectory generation for corrective polishing of freeform surfaces.

4. Results and discussion

4.1 Taguchi analysis of simulation experiments for optimizing the process parameters

The average removal depth of polished surface topography is an important criterion for quantifying the polishing performance when corrective polishing of freeform surfaces with the consideration of time efficiency and surface quality improvement. The average removal depth is commonly determined based on a calibration, which is a very time-consuming procedure and may produce scrap. Hence, a process simulation is crucial for determining an optimum set of polishing parameters prior to running the process. In this study, a series of simulation experiments was conducted by Taguchi trials in order to identify optimized process parameters for form correction. Table 1 and Table 2 show the six fixed process parameters and three control factors, respectively. Accordingly, the Taguchi design method was arranged in an L_9 Orthogonal Array.

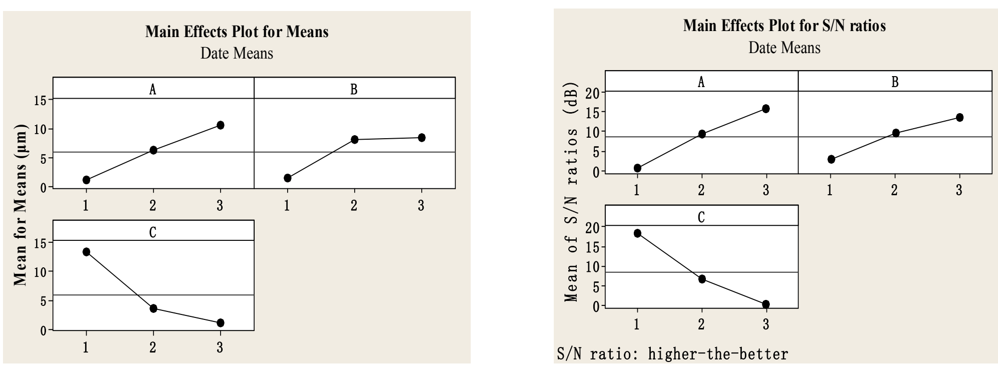
Table 1. The fixed process parameters in Taguchi design of simulation experiments

Fixed factors	Levels	Fixed factors	Levels
Tool radius	20 mm	Surface feed	50 mm/min
Tool pressure	1.2 bar	Particle property	3.22 μm (Al_2O_3)
Head speed	1200 r/min	Polishing cloth	LP-66

Table 2. The control factors and levels in Taguchi design of simulation experiments

No.	Control factors	Levels		
		1	2	3
A	Process angle (°)	5	10	15
B	Tool offset (mm)	0.1	0.2	0.3
C	Polishing spacing (mm)	0.5	1.0	1.5

In these simulation experiments, a higher-the-better signal-to-noise (S/N) ratio was used and a larger S/N ratio infers that the corresponding factor level setting provides a higher polishing efficiency in the form correction process. Figures 6(a) and Fig. 6(b) show the plots of the means and S/N ratios for the average removal depth in graphical form, respectively. Both of them indicate that the combination of the optimal factor level for the average removal depth is A3B3C1. It is interesting to note that the polishing spacing, precess angle and tool offset are critical factors in descending order which affect the average removal depth and hence the polishing efficiency. To confirm the reliability of the Taguchi experiments, simulation experiment was performed under the optimal operational parameters obtained from the Taguchi designed experiments. The predicted value of 30.58 by Taguchi trials is basically the same with the value of 31.26 by the model-based simulation system. As a result, the optimal process parameters are given as the polishing conditions for the subsequent corrective polishing experiments, which are pressure angle of 15°, tool offset of 0.3 mm and polishing spacing of 0.5 mm.



(a) (b)

Fig. 6. (a) mean and (b) S/N ratio factor response graphs for the average removal depth.

4.2 Experimental verification of form correction process for sinusoidal surface

The sinusoidal workpiece was mounted on the C axis of the Zeeko IRP200 polishing machine and the surface was measured using the on-machine metrology system with a laser sensor. The scanning time was about 5.2 hours for a surface of 30 mm× 30 mm and the measurement data of the initial surface was acquired in a point cloud format with the number of 3721 points. The scanning time can be shortened by increasing the feed rate and decreasing the dwell time on each sampling point. The measured data of initial surface was registered to the original data of the design surface by using an iterative closest point (ICP) method [19]. The deviation of the measured surface to the designed surface is the error map of the initial surface, which should be removed in the form correction process, as shown in Fig. 7(a).

Based on the information of error map distribution, the dwell time map along the tool path was determined by a modified least square QR decomposition (LSQR) method and implemented by the G-code program for the polishing machine. Figure 7(b) shows the calculated dwell time distribution and Fig. 7(c) shows the raster polishing path for corrective polishing of the sinusoidal surface. After the first round corrective polishing, the polished sinusoidal surface was measured by the on-machine metrology system and the error map of

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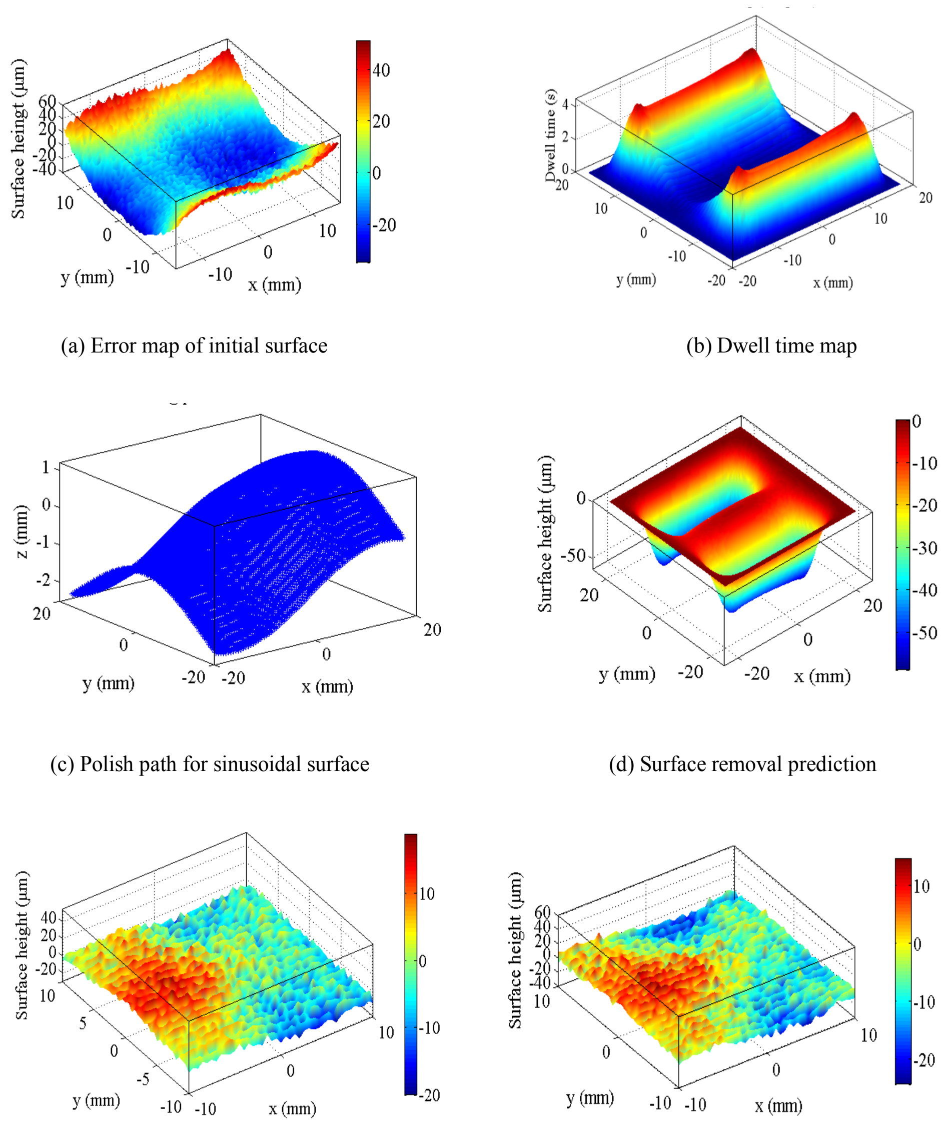
measured surface was shown in Fig. 7(f). Figure 7(d) shows the predicted surface removal map which is calculated by the cumulative process of dwell time map and the influence functions and Fig. 7(e) presents the error map of predicted result of polished surface which is calculated by the model-based simulation model.



(a) Error map of initial surface
(b) Dwell time map
(c) Polish path for sinusoidal surface
(d) Surface removal prediction
(e) Error map of predicted surface
(f) Error map of measured surface

Fig. 7. The form correction process of freeform polishing of sinusoidal surface.

Table 3 summarizes the peak-to-valley (Rt) value and root mean squared (Rq) value of error map of the measured and predicted surface for corrective polishing of sinusoidal surface. The Rt value of the form error of the sinusoidal surface was improved from 85.6 µm to 38.9 µm after 1 polishing cycle with total dwell time of 1.9 hours. In addition, the Rq value of the form error was reduced from 18.9 µm to 7.5 µm and the convergence rate of Rq

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value is about 60%. It is found that the Rt value and Rq value of error map of prediction result of polished surface was 38.7 μm and 7.3 μm, respectively. It is interesting to note that the simulated result agrees well with the measured data. The comparison results show that the form error of the sinusoidal surface was significantly improved by the proposed self-optimization polishing system and the model-based simulation system can be successfully used for the prediction and better understanding of the form correction process.

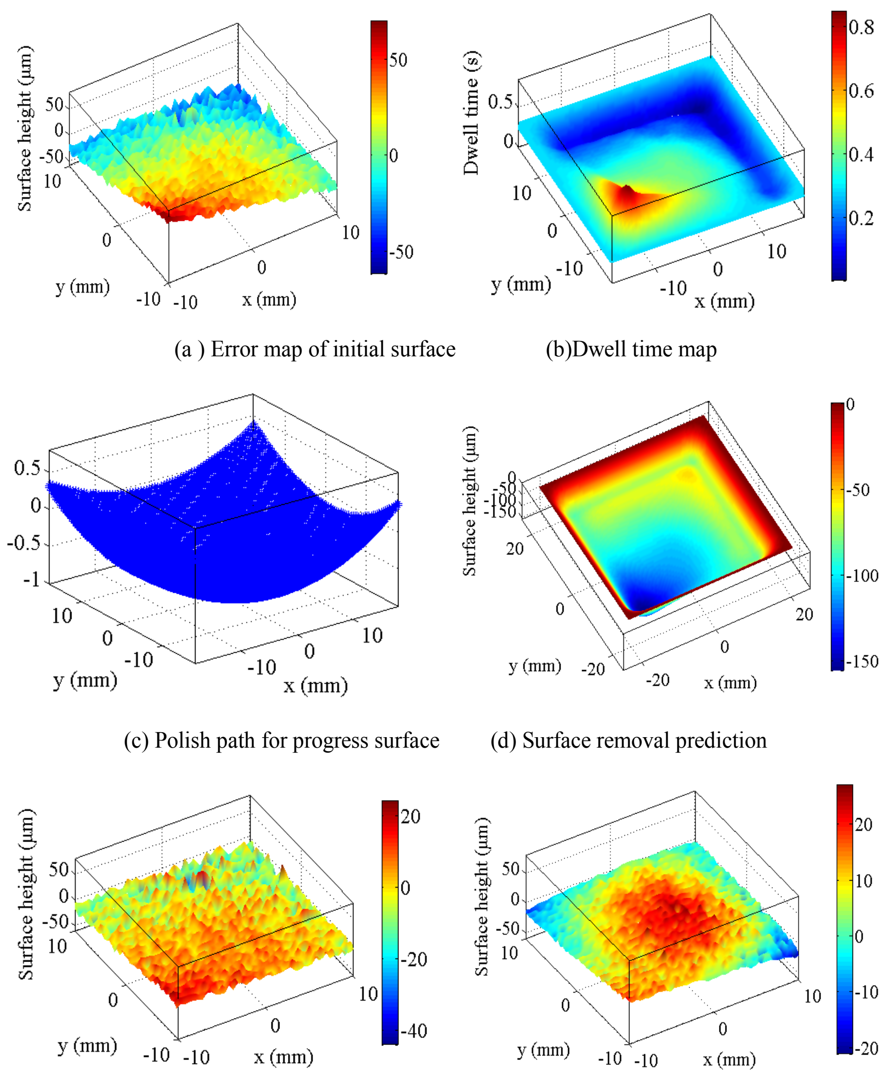
Table 3. The peak-to-valley (Rt) value and root-mean-square (Rq) value of the form error for corrective polishing of sinusoidal surface

Evaluation Items	Error map of measured data of initial surface	Error map of measured result of polished surface	Error map of prediction result of polished surface
Rt value(μm)	85.6	38.9	38.7
Rq value(μm)	18.9	7.5	7.3

4.3 Experimental verification of form correction process for progressive lens surface

Figure 8(a) shows the error map of measured data of initial progressive lens surface. The calculated dwell time map and the polishing path for corrective polishing of the progressive surface are shown in Fig. 8(b) and Fig. 8(c), respectively. The polishing path with the information of dwell time map was implemented by the G-code program for the polishing machine. Figure 8(f) shows the error map of measured data of the progressive lens surface after the first round corrective polishing, while Fig. 8(d) shows the predicted surface removal map and Fig. .8(e) presents the error map of predicted result of polished surface. Table 4 provides the peak-to-valley (Rt) value and root-mean-square (Rq) value of error map of the measured and predicted surface for corrective polishing of progressive lens surface. The progressive lens surface was finished from the Rt value 131.6 μm and Rq value of 21.8 μm to the Rt value 48.2 μm and Rq value of 7.9 μm with total dwell time of 0.4 hour. While the simulated result with Rt value of 53.8 μm and Rq value of 8.3 μm shows a good agreement with the measured data. In practice, polishing is a multi-step process conducted by repeatedly running particular designed polishing cycles until the expected surface finish and form error are obtained. Within each cycle, the polishing tool sweeps through the polished surface following the adopted polishing tool path and desired dwell time map. Although the error map after fabrication is still relatively large, it could be further reduced by more corrective runs. Since the measurement accuracy is affected by the machine motion error which is in the level of several micrometers (i.e.it is interesting to note that the motion error is not highly affected for the polishing process due to the nature of the polishing process), polishing the workpiece to sub-micrometer level is difficult at this setup. However, the method proposed in the paper is well demonstrated and polishing the workpiece to sub-micrometer will be conducted in future work with a better measurement method.

Automation of corrective polishing of optical freeform surfaces is not an easy task, especially if it is difficult or impossible to measure the process variables or surface condition while the process is running. However, in order to remove the surface error-profile of freeform surfaces with high efficiency, this paper presents an integrative study of a model-based self-optimization method for automatically achieving the motion control and form correction in CCBP. The mode-based self-optimization method employs a model-based simulation system to transfer expert knowledge together with on-machine measurement data and optimization simulations into dwell time algorithm for an increase in robustness and efficiency of corrective polishing of freeform surfaces with respect to surface quality. The experimental results demonstrate that the proposed self-optimization system can be successfully used for optimizing, measuring and predicting the form error of the freeform polishing. Moreover, the proposed method allows the time-variant influence functions to be optimized during the polishing process and hence further improve the convergence rate of the form error compensation process and avoid the expensive trial-and-error approach. To further improve these results, future work will be conducted by using continuous precessing bonnet polishing for final super-smooth finishing of the optical freeform surfaces. In addition, the self-optimization algorithm and tool path optimization will be further studied for improving the sustainable convergence over a series of corrective runs with a high polishing efficiency.



(a) Error map of initial surface (b)Dwell time map

(c) Polish path for progress surface (d) Surface removal prediction

(e) Error map of predicted surface (f) Error map of measured surface

Fig. 8. The form correction process of freeform polishing of progressive lens surface.

Table 4. The peak-to-valley (Rt) value and root-mean-square (Rq) value of the form error for corrective polishing of progressive lens surface

Evaluation Items	Error map of measured data of initial surface	Error map of measured result of polished surface	Error map of prediction result of polished surface
Rt value(μm)	131.6	48.2	53.8
Rq value(μm)	21.8	7.9	8.3

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5. Conclusions

In this paper, a model-based self-optimization system has been developed for corrective polishing of optical freeform surfaces, which is established based on modelling and simulation of polishing processes, error compensation, on-machine metrology and dwell time control algorithm. Firstly, Taguchi design of simulation experiments were conducted using the model-based simulation system for determining an optimum set of polishing parameters prior to running the form correction process. Hence, an on-machine metrology system was integrated together with a freeform surface characterization method built based on an iterative closest point (ICP) algorithm, which enables the in situ measurement capability of optical freeform surfaces for supporting in process compensation of machining errors. After that, an inverse model has been developed to determine the dwell time on each track point along the polishing path so as to remove the residual materials from the surface error-profile. With the availability of such information, the numerical control (NC) program was generated by the purposely built tool path generator for guiding the polishing module across the workpiece surface, while the surface generation of the optical freeform surface after corrective polishing was predicted by the model-based simulation system.

A series of simulation and practical experiments were conducted on sinusoidal and progressive lens surfaces so as to verify the performance of the model-based self-optimization system. The form error of the sinusoidal surface was found to be improved from 85.6 μm for the Peak-to-valley (Rt) value and 18.9 μm Root-mean-square value (Rq) to 38.9 μm for Rt and 7.5 μm for Rq after 1 polishing cycle of corrective polishing with a total dwell time of 1.9 hours. The progressive surface was finished from the Rt value of 131.6 μm and Rq value of 21.8 μm to the Rt value of 48.2 μm and Rq value of 7.9 μm with a total dwell time of 0.4 hour. It is interesting to note that the convergence rate of the Rq value of the sinusoidal surface and the progressive lens surface is more than 60%. Moreover, it was also found that the simulated results agree well with the measured data in the form correction process. The comparison results infer that the proposed method can be successfully used for optimizing, measuring and predicting the form correction in computer controlled bonnet polishing (CCBP). To further improve the results, future work will be undertaken by using continuous precessing bonnet polishing and force-controlled end-effector for final super-smooth finishing. In addition, the self-optimization algorithm and tool path optimization should be further studied for improving the polishing efficiency.

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