Study on the Heat and Pressure and Their Effect on the Surface Shape Precision of Optic in Continuous Polishing

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Abstract. In the process of ring polishing, the non-uniform temperature distribution in the element will make the shape of the element change greatly, which leads to the non-uniform pressure distribution between the element and the pad. According to Preston equation, uneven pressure distribution will produce uneven material removal rate and affect the surface morphology of optics. In this paper, the influence of temperature difference on the deformation of the element is revealed, and then the relationship between the deformation and the contact pressure of the element is deduced. Combined with Preston equation, the temperature difference in the element and the surface accuracy of the element are finally connected, and verified by the surface shape measurement.

1. Introduction

Optical polishing processes are typically classified into two kinds, one is the full-aperture polishing processes using a lap which is substantially larger than the optical elements being polished [1], while the other is the sub-aperture polishing processes using a small tool which removes local material at a time [2, 3]. The full-aperture polishing processes uses a large substrate platen covered with a polishing layer such as pitch, polyurethane and felt materials. Using the pitch lap is commonly called Continuous Polishing (CP) process [4]. The introduction of polyurethane pad in 1990s, as a substitution for pitch, makes full-aperture polishing easy to use high speed and pressure, giving a high removal rate without concern for flow in the pitch.

The CP machine uses a large substrate platen made from good thermo stable materials such as granite, as shown in Fig. 1. An annular pitch layer is prepared on the granite plate surface as the polishing lap. Grooves are machined of the pitch lap so as to improve the fluidity of the pitch lap and transmission of the slurry. On one side of the annulus are two to three work rings whose inside diameter matches the annulus width. The flat optical elements to be polished are placed on the pitch lap in metal or phenolic septums within these rings. On the remaining portion of the annulus is a large circular truing tool called ‘conditioner’, which is substantially wider than the annulus. During CP processes, the polishing lap, work rings and conditioner are driven by servo motor to rotate counterclockwise at a nearly synchronous rate. The abrasive slurry is sprayed by a nozzle onto the lap surface and transported to the polishing site by the grooves. From the combination of the chemical and
mechanical actions of the slurry, micro/nano material removal takes place, enabling surface finishing to be realized [5, 6].

Figure 1. Schematic of a typical CP polisher with a pitch lap.

The key point for the CP process is to control the surface figure of the optical elements in a determined manner, especially for a high precision surface figure [7]. However, the control process still depends on operators’ skills to achieve the target surface figure, which is far from to be a determined process [8]. Determination of the surface shape of the pitch lap has been a challenge till now.

Temperature is always an important factor in precision machining. The deformation caused by temperature difference often exceeds the machining accuracy required by the workpiece. Yasa a. samprino proposed a method to roughly obtain the temperature of the contact surface between the workpiece and the pad during the processing [9]. In this method, the upper surface temperature of the workpiece is measured in real time by a thermal imager, and then the temperature distribution of the contact surface is obtained by combining the thermal diffusion coefficient of the workpiece material. The results show that the surface temperature of workpiece is higher than that of asphalt pan, and the temperature distribution of contact surface is affected by the velocity of polishing fluid. Jeng haurhorn [10] studied the influence of polishing wax plate and polishing solution on the temperature rise during the processing. The results show that with the increase of particle size, density, hardness and roughness coefficient of polishing powder, the temperature rise increases. The change of temperature has nothing to do with the hardness of workpiece. David white established the temperature model of polishing process, and measured the temperature of the pad surface with a thermal imager [11]. The temperature of the contact surface in the polishing process can be considered as a dynamic system. In order to establish a framework to describe the heat generation and loss in the process, they assume that the heat generated in the polishing process is mainly transmitted through the heat conduction of the polishing pad and the polishing fluid. Then the first-order model is used to explain the generation and dissipation of heat in the polishing process, and the flow rate of polishing fluid is measured to calculate the heat taken away by the polishing fluid. The results show that the heat generated by polishing is approximately equal to the temperature lost through the asphalt pan and polishing solution. Nam Hoon Kim studied the influence of air conditioning temperature and ambient temperature on polishing process [12, 13]. It is found that the environmental temperature has a great influence on the removal efficiency of the workpiece.

The influence of temperature difference on the deformation of the element is revealed, and the relationship between the deformation and the contact pressure of the element is deduced in section 2. Combined with Preston equation, the temperature difference in the element and the surface accuracy of the element are finally connected, and verified by the surface shape measurement in section 3.

2. Deformation caused by non-uniform temperature distribution
In the process of ring polishing, the material removal is achieved by friction between the element and the polishing pad. In the process of friction, the contact surface between the element and the pad will
generate heat, which can not be dissipated by convection, heat conduction and other forms in time, so these heat will be transferred into the element, which will cause the local temperature rise of the element and uneven temperature distribution in the element. Due to the expansion and contraction of heat, the volume of the area with high temperature in the element will expand, which will change the shape of the element and bring uncertainty to the machining results of the ring polishing. In the process of ring casting, in the thickness direction of the optical element, the temperature of the machined surface (lower surface) of the element is usually higher than that of the back (upper surface) of the element. This temperature distribution causes the edge of the element to rise and the center of the element to bulge down, as shown in Figure 2.

![Figure 2. Cross section diagram of element thermal deformation.](image)

2.1. Calculation of deformation caused by temperature difference

The temperature difference in the thickness direction of the element will cause the edge of the element to rise, and the deformation can be deduced from the formula of thermal expansion and cold contraction.

\[
\Delta h = \frac{\alpha \Delta t r}{d} dt
\]

Where R is half of the radius or maximum length of optical element; d is thickness; \( \alpha \) - coefficient of thermal expansion; and t is the temperature difference in thickness direction.

Integrate the left and right sides of the equation:

\[
\Delta H = \int_0^r \alpha \times \Delta t \times \frac{r}{d} dr = \frac{\alpha \Delta t r^2}{2d}
\]

2.2. Pressure distribution caused by heat deformation

Heat stress in the vertical direction is equal to the product of the deformation of the element and the elastic modulus.

Heat stress

\[
\sigma = Er^2 \alpha \Delta t / 2d^3
\]

E is the elastic modulus of the element

Since the edge of the element is warped after deformation, the stress is concentrated in the center of the element. At the same time, the total pressure of the optic to the pad is equal to the gravity of the optic itself.

Optic single point gravity G:

\[
G = \rho h
\]

When \( G > G \), the element deforms. So there is a point R1 on the element where the thermal stress is equal to gravity.
It is defined that $r_1$ is the critical point of deformation, and the component outside the component $r > r_1$ does not contact the pad, as shown in Fig.3.

![Figure 3. Deformation of the opcic.](image)

3. The relationship between heat and contact pressure

The relationship between the pressure $F_n$ and the temperature difference in the element is deduced in general form. Because the deformation of the element is a quadratic function of $r$, so the pressure is also a quadratic function of $r$.

$$F_n = mr^2 + n$$  \hspace{1cm} (6)

When the critical point is at element edge $r_0$.

$$\rho h \times 2r_0 = \int_{r_0}^{r} (mr^2 + n) dr$$  \hspace{1cm} (7)

$R_0$ is the radius of the element, $h$ is the thickness of the element.

$$F_n = mr^2 + \rho h - \frac{m}{3} r_0^2$$  \hspace{1cm} (8)

Integrate both sides of eq.7.

$$\int_{r_0}^{r} mr^2 + \rho h - \frac{m}{3} r_0^2 dr = 2r_0\rho h$$  \hspace{1cm} (9)

$$F_n = (1 - \frac{3r^2}{r_0} + \frac{r_0^2}{r^2 + r_0^2}) \rho h \left( r_0 = \sqrt{\frac{2\rho h}{\alpha \Delta T E}} \right)$$  \hspace{1cm} (10)

Here, the positive pressure is only related to the temperature difference of the element

3.1. Surface shape measurement experiment

According to the relationship between pressure and temperature difference. When there is a temperature difference in the element, the pressure in the center of the element increases. According to Preston formula:

$$MRR = K \cdot P \cdot V$$  \hspace{1cm} (11)
Material removal rate is also high in places with high pressure. MRR is the material removal rate, $K$ is the coefficient, $P$ is the pressure, $V$ is the relative speed of the optic and the pad. Therefore, the surface shape result of the element is usually concave. We measured the surface shape of K9 element with length of 600 and width of 480 after polishing. In the process, we measure the temperature difference of 0.3°C. According to eq.10, the concave surface of the element is 1.32m. And the surface shape test result of the component after machining is also 1.4m, as shown in Fig.4. The accuracy of the conjecture is proved.

**Figure.4.** Surface shape.

### 4. Conclusion
The deformation formula and Preston equation through thermal expansion and cold contraction. The relationship between temperature difference and pressure is obtained. Similarly, the surface shape of the element can be predicted according to the temperature difference inside the element. This assume has been verified by experiments.

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