ОПТИЧЕСКОЕ МАТЕРИАЛОВЕДЕНИЕ И ТЕХНОЛОГИЯ

SMOOTHING EVOLUTION MODEL FOR COMPUTER CONTROLLED OPTICAL SURFACING

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A polishing pad can smooth out mid-to-high spatial frequency errors automatically due to its rigidity and modeling of the smoothing effect is important. The relationship between surface error and polishing time is built here based on Bridging model and Preston's equation. A series of smoothing experiments using pitch tools under different motion manners were performed and the results verified exponential decay between surface error and smoothing time. At the same time, parameters describing smoothing efficiency and smoothing limit were also fitted from the results. This method can be applied to predict the smoothing effect, estimate the smoothing time and compare smoothing rates of different runs.

Key words: *Computer Controlled Optical Surfacing, mid-to-high spatial frequency errors, smoothing efficiency, smoothing evolution model.*

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1. Introduction

Controlling and correcting mid-to-high spatial frequency errors on optical surfaces is critical for modern optical systems such as Extreme Ultra-Violet Lithography [1] and inertial confinement fusion system like National Ignition Facility [2]. The final performance of these optical systems will be greatly influenced by mid-to-high spatial frequency errors as these errors are directly related to the sharpness of optical system and the laser induced damage threshold value of optics under high power laser. Today, peak-to-valley (PV) and root-mean-square (RMS) are no longer the only criterion to evaluate an optical surface anymore, instead structure function and power spectrum density which both are the function of spatial frequencies are more widely used as the target specification [3].

Smoothing is a convenient and efficient way to correct mid-to-high frequency errors. Existing published papers have tried to mathematically describe the smoothing process. Brown and Parks [4] proposed a quantitative smoothing model for elastic backed lapping belt. Jones [5] analyzed the smoothing effect of a pitch tool and developed a numerical method to simulate the smoothing process. Mehta and Reid [6] investigated the smoothing effect of a flexible polishing tool using Bridging model. Kim [7] developed a parametric smoothing model to describe the smoothing efficiency of visco-elastic polishing tools such as pitch laps and RC lap.

Kim's model is simple and effective, but actually the model simply gives the averaging SF while neglecting the instantaneous property, which is disclosed in our model that describes evolution of surface error with time during smoothing process in computer controlled optical surfacing (CCOS) by using the limit. In this paper, a model describing the evolution of surface error with time during smoothing process is deduced based on Preston equation and the Bridging model, then a set of experiments is conducted to verify the model.

2. Theoretical model

When polishing mirror with an elastic tool (*e.g.* a pitch tool with stainless steel back plate), the tool stiffness is a key factor which influences the pressure distribution between tool and workpiece. For one-dimensional case, the polishing pressure distribution $P(x)$ induced by sinusoidal errors *error(x)* on the surface of workpiece can be given based on the Bridging model as [7]:

$$error(x) = PV\sin(2\pi\xi x) \quad (1)$$

$$P(x) = P_{\text{nominal}} + \kappa_{\text{total}} \cdot error(x) \quad (2)$$

where PV is the peak-to-valley (PV) magnitude of the sinusoidal error, ξ is the spatial frequency of the surface error, P_{nominal} is the nominal pressure under the tool, κ_{total} is the compressive stiffness of the whole tool including elastics material and polishing interface material (here assuming the tool can touch peak and valley of the error at the same time). From Eq. (2) it's clearly seen that pressure is higher at peak point. Based on the distribution of pressure and Preston equation, the evolution of smoothing process will be given as follows.

If initial surface is expressed by $E_0(x)$ (here $E_0(x) = E_0\sin(2\pi\xi x)$, E_0 is the PV magnitude of $E_0(x)$), after smoothing for duration of t, surface profile changes to $E_t(x)$ (it's defined similar to $E_0(x)$, *i.e.*, $E_t(x) = E_t \sin(2\pi\xi x)$). We can divide smoothing period t into n intervals whose length is Δt, then surface after every Δt can be noted as $E_1(x)$, $E_2(x)$, $E_3(x)$, ..., $E_n(x)$ (they are defined similar to $E_0(x)$ and $E_n(x) = E_t(x)$). When n is big enough, then Δt is short enough, polishing parameters can be treated as constants in this short interval and Preston equation can be employed in analyzing smoothing processes.

During smoothing for duration of Δt, a layer of material is uniformly removed from the workpiece. According to Preston equation, material removal is proportional to pressure and relative speed between tool and workpiece. The relative speed is kept the same all over the workpiece, but from Eq. (2) we can see the pressure is different form peak point to valley point, so after smoothing the surface error will change. At peak points, more material is removed due to additional pressure which can be expressed as:

$$P_{\text{add}}(x) = P_0(x) - P_{\text{nominal}} = \kappa_{\text{total}} E_0(x), \quad (3)$$

here $P_0(x)$ is pressure induced by initial surface error $E_0(x)$.

Material removal during smoothing for Δt can be calculated from Preston equation as:

$$MR = k_{\text{Preston}} P_0(x) V \Delta t \quad (4)$$

here MR is material removal, k_{Preston} is Preston coefficient, V is relative speed between tool and workpiece and it is kept the same all over the surface. The PV magnitude change of $E_0(x)$ should be the removal at peak point subtracts the removal at valley point which is:

$$\begin{gathered} E_C = MR_{\text{peak}} - MR_{\text{valley}} = \\ = k_{\text{Preston}} P_{\text{peak}} V \Delta t - k_{\text{Preston}} P_{\text{vallye}} V \Delta t = \\ = k_{\text{Preston}} 2E_0 \kappa_{\text{total}} V \Delta t, \end{gathered} \quad (5)$$

here E_C is PV magnitude change of $E_0(x)$, MR_{peak} is material removal at peak point, MR_{valley} is material removal at valley point. After smoothing for Δt, $E_0(x)$ changes to $E_1(x)$, so PV magnitude of $E_1(x)$ is given by

$$\begin{gathered} E_1 = E_0 - k_{\text{Prerston}} 2E_0 \kappa_{\text{total}} V \Delta t = \\ = E_0 (1 - K_{\text{Prerston}} \kappa_{\text{total}} \Delta t). \end{gathered} \quad (6)$$

As speed V only affect material removal efficiency and doesn't change during smoothing process, all constants describing smoothing efficiency can be integrated into Preston coefficient and the amended Preston coefficient is then K_{Preston}.

Keep repeating this process, and then surface error after t is

$$\begin{gathered} E_n = E_0 (1 - K_{\text{Prerston}} \kappa_{\text{total}} \Delta t)^n = \\ = E_0 \left((1 - K_{\text{Prerston}} \kappa_{\text{total}} \Delta t)^{\frac{1}{\Delta t}} \right)^t. \end{gathered} \quad (7)$$

Surface after smoothing for t can be obtained by taking the limit as $\Delta t \to 0$:

$$\begin{gathered} E_t = E_n = \lim_{\Delta t \to 0} E_0 \left((1 - K_{\text{Prerston}} \kappa_{\text{total}} \Delta t)^{\frac{1}{\Delta t}} \right)^t = \\ = E_0 e^{-K_{\text{Prerston}} \kappa_{\text{total}} t}. \end{gathered} \quad (8)$$

It's clearly seen from Eq. (8) that surface error reduces exponentially with time as smoothing goes on. The decay rate reflects smoothing rate and correlates to material removal rate and rigidity of tool.

As smoothing process goes on, surface error becomes smaller and smaller, that will result in smaller additional pressure at high peaks. At this time, the fluid dynamics of polishing compound may limit the effect of smoothing and this will result in a smoothing limit.

During practical application, smoothing process can be described by this parametric model:

$$E_t = E_0 e^{-kt} + E_f, \qquad (9)$$

here E_t is surface PV error after t, E_0 is initial surface PV error, k is a parameter representing smoothing rate and E_f is final smoothing limit. These parameters can be fitted from experimental data and this model can be easily applied to predict surface error at different time of smoothing process and compare smoothing efficiencies of different smoothing processes.

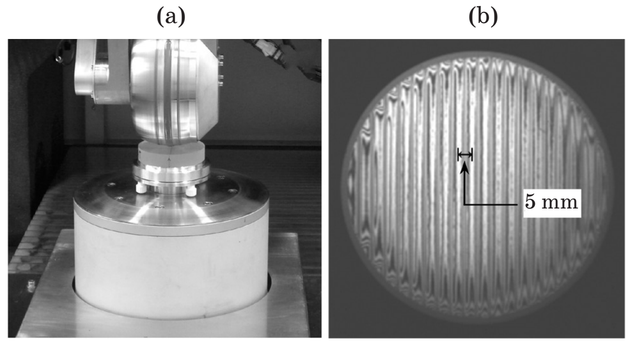

Fig. 1. MRF polishing to generate the ripples (a) and the intensity map of the fused silica sample with sinusoidal ripples (b).

3. Experiments and results

3.1. Experimental Set-up

Two sets of experiments with pitch tools under different motion manners were done to validate the model and at the same time to compare the smoothing efficiencies of different motion manners. Details of the set-up are provides in Table 1.

Two types of tool motion, orbital motion and epicyclic motion, were used in this paper:

– Orbital: The tool orbits around the TIF (Tool Influence Function) center with an orbital radius and does not rotate;

– Epicyclic: The tool orbits around the TIF center and rotates about the center of the tool.

The details of the operation conditions are presents in Table 2.

Table 1. Experimental set-up for the smoothing experiment

Parameter	Pitch Tool
Tool diameter	25 mm
Stainless steel back plate thickness	4 mm
Elastic material	64# pitch
Elastic material thickness	5 mm
Polishing interface	Pitch itself

A sinusoidal ripple with spatial frequency $\xi = 1/5 = 0.2$ mm^{-1} and $PV \approx 1.1$ μm was generated on a 100 mm diameter fused silica workpiece. MRF (Magnetorheological Finishing) technology, a highly deterministic figuring method, was employed to generate the ripples as presented in Fig. 1a. The generating of ripples is basically the same as usual MRF figuring process and the only difference is the target map is sinusoidal ripples here instead of a perfect plane. The ripples were measured by a Zygo GPI interferometer and the result was shown in Fig. 1b.

3.2. Results

The pad scanned at a uniform speed of 800 mm/min during smoothing processes of two motions, thus a uniform layer of material would be removed at one scan which cost about 5 minutes.

After each scan, the workpiece was measured by the same interferometer mentioned before. Some measured profiles are shown in Fig. 2. The decrease of the ripple magnitude as the smoothing time increases is clearly demonstrated, which means pitch pads did smooth out these high-frequency ripples. The orbital motion (a) spent

Table 2. Experimental set-up for the smoothing experiment

Tool motion	Orbital tool motion	Epicyclic tool motion
Orbital radius	5 mm	5 mm
Tool orbit-motion rpm	150 rpm	150 rpm
Tool self-rotation rpm	----	155 rpm
Workpiece	Φ100 mm fused silica	Φ 100 mm fused silica
Nominal polishing pressure	0.15 MPa	0.15 MPa
Polishing compound	Ceria	Ceria
Polishing compound particle size	0.5 μm	0.5 μm

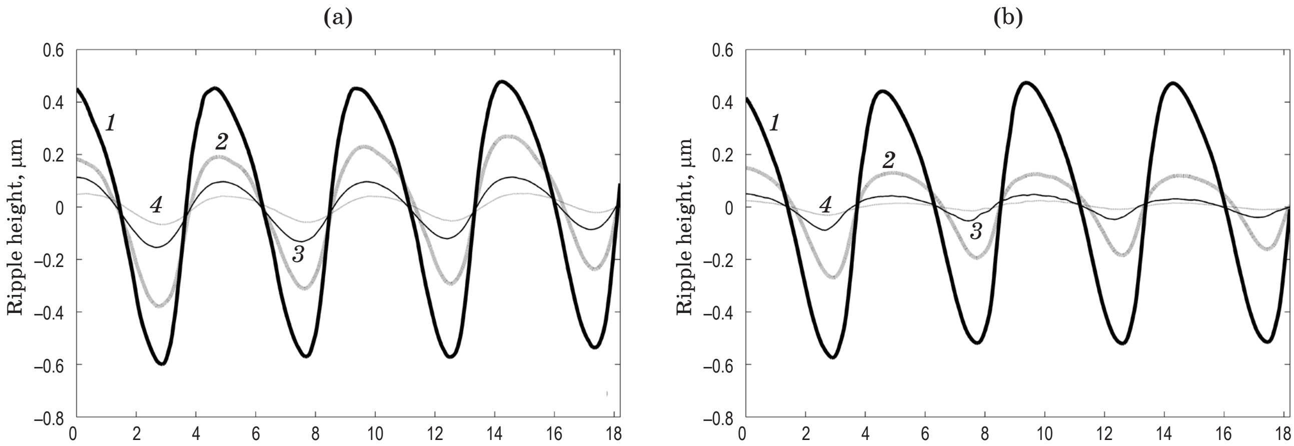

Fig. 2. Measured profiles of ripple as tool smooth out the ripples. a – orbital motion: *1* – $t = 0$, *2* – $t = 20$ min, *3* – $t = 40$ min, *4* – $t = 60$ min; b – cpicyclic motion: *1* – $t = 0$, *2* – $t = 5$ min, *3* – $t = 10$ min, *4* – $t = 15$ min.

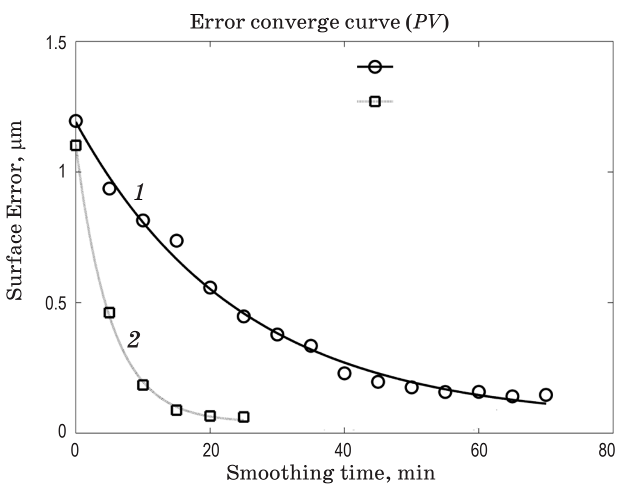

Fig. 3. Measured surface error vs. smoothing time and fitted smoothing curve: *1* – orbital motion, $E = 1{,}14e^{-0{,}04t} + 0{,}05$; 2 – epicyclic motion, $E = 1{,}06e^{-0{,}19t} + 0{,}04$.

about 60 minutes in smoothing out the ripples while the epicyclic motion (b) spent about only 15 minutes, which was much faster than orbital motion.

Experiments were performed until no obvious reduction in the magnitude of the ripple was observed. The experimental results are shown in Fig. 3 and the smoothing curves were also fitted using parametric model in Eq. (7). The parametric model fits the experiment result quite well. The fitted parameters are presented in Table 3.

Table 3. Parameters for parametric model

Type of tool motion	E_0, μm	k, min^{-1}	E_f, μm
Orbital motion	1.14	0.04	0.05
Epicyclic motion	1.06	0.19	0.04

3.3. Discussion

As the initial magnitudes of ripple in two experiments were basically the same, so the initial errors E_0 for both situations were quite close to each other. The k which reflects smoothing rate of epicyclic motion was much bigger than that of orbital motion. This was inconsistent with the result that epicyclic motion smoothed faster than orbital motion as shown in Fig. 2. As these two motions employed the same pitch pad during smoothing, this difference of smoothing rates may lie in the difference of motion type. During epicyclic motion the polishing pad orbits and rotates at the same time, which means epicyclic motion will remove more material and formed a more complex trajectory than orbital motion when other conditions are kept the same, so epicyclic motion shows a higher smoothing rate than orbital motion.

The smoothing limits E_f for both cases were close to each other and this could be explained by the same pitch lap used in two motions. Just as we mentioned before, the existence of smoothing limit was mostly due to the small additional pressure on peaks. The pressure distribution nonuniformity is mainly affected by the distribution of surface error and the property of polishing tools. Two motions used the same pitch tool, so the pressure distribution should be the same when facing the same error distribution. Thus the smoothing limits of these motions must be the same. The small difference of smoothing limits under orbital motion and epicyclic motion may come from the instability of the smoothing process or measurement error.

Conclusion

A smoothing evolution model is deduced from Bridging model and Preston's equation. A set of experiments was done to validate the model. From previous discussion we can conclude:

1. This model explicitly describes the exponential decay of *PV* magnitude of surface error with time during smoothing processes. It can be applied to predict the smoothing effect and estimate the smoothing time.

2. This model integrates factors which will affect the smoothing rate such as stiffness reflecting structure property of tool and removal rate reflecting chemo-mechanical property and movement motions of tool, so it can describe the smoothing effect more sufficiently. It can be used to compare the smoothing efficiencies of different smoothing processes with different tools or different smoothing parameters.

3. Smoothing experiments between orbital motion and epicyclic motion are compared and the results show epicyclic motion smooth about 5 times faster than orbital motion. Epicyclic motion can be applied in smoothing to improve the smoothing efficiency.

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