Development of a Computer-Controlled Polishing Process for X-Ray Optics

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ABSTRACT

The future X-ray observatory missions require grazing-incidence x-ray optics with angular resolution of < 5 arcsec half-power diameter. The achievable resolution depends ultimately on the quality of polished mandrels from which the shells are replicated. With an aim to fabricate better shells, and reduce the cost/time of mandrel production, a computer-controlled polishing machine is developed for deterministic and localized polishing of mandrels. Cylindrical polishing software is also developed that predicts the surface residual errors under a given set of operating parameters and lap configuration. Design considerations of the polishing lap are discussed and the effects of nonconformance of the lap and the mandrel are presented.

Keywords: X ray optics, computer controlled polishing, cylindrical polishing, mid-spatial frequency errors,

1. INTRODUCTION

International X-ray Observatory (IXO) requires grazing incidence replicated optics of large collecting area (3 m^2) in combination with angular resolution of < 5 arcsec half-power diameter (HPD)[1]. Typical mirror shells fabricated to date at Marshall Space Flight Center (MSFC) have HPDs in 13-15 arcsec range[2].Efforts are being made to increase their angular resolution to meet the demand of 5 arcsec. The achievable resolution depends on the quality of the mandrels from which the mirror shells are being replicated. Mandrel fabrication process involves electroless nickel-phosphorous coating, single point diamond turning, polishing, deposition of electroless Ni shell on the mandrel, and separation of Ni shell by differential thermal contraction. The overall quality of mandrel will be the cumulative effects of the all these processes. Technology enhancements for every process are needed to improve the current resolution of the shell mirrors[3].

The present work concentrates on improving upon the polishing step of the mandrel fabrication process. The basic idea on working on the polishing step is that by using deterministic and localized polishing, the errors arising from the earlier step i.e precision machining can also be corrected. This objective demands the development of a computer controlled polishing machine for cylindrical mandrels. The machine should be capable of removing material on nanometer scale in a deterministic and localized fashion. The study focuses on establishing a relationship between the polishing process parameters and the mid spatial-frequency error generation, which is crucial for developing better quality mandrels. The process parameters are speeds of lap and mandrel, tool's influence function, contour path (dwell) of the tools, tools shape and their distribution on the polishing lap.

Section 2 discusses the causes of mid spatial-frequency error generation during polishing operation. Most of the causes are inherent of the polishing process itself. The design consideration of the polishing lap to optimize the process is presented in Section 3. The polishing simulations are performed and power spectral density distributions are computed as an evaluating parameter for the surface axial and circumferential profiles. Effects of influence function on the achievable profile accuracy are shown in Section 4. Gaussian and asymmetric influence functions have been chosen to discuss the effects. Section 5 gives the current status of the experiment and briefly describes the recently developed computer controlled polishing machine.

2. CAUSES OF GENERATION OF MID SPATIAL-FREQUENCY ERRORS

A typical optical manufacturing process for mandrel consists of diamond turning or precise grinding and a subsequent polishing process to remove residual tool marks and other deviations. Unlike the conventional polishing process for spherical optics where optics and polishing tool rotates around a common axis, the polishing mechanism for cylindrical optics requires a rotation of optics and a small back and forth axial motion of polishing tool. Kinematics of such a polishing process is shown in Fig.1. A workpiece of diameter D rotates at constant angular velocity and a polishing lap of approximately the same length as the mandrel moves back and forth linearly. The lap is held in contact with the surface by using gravity as a force.

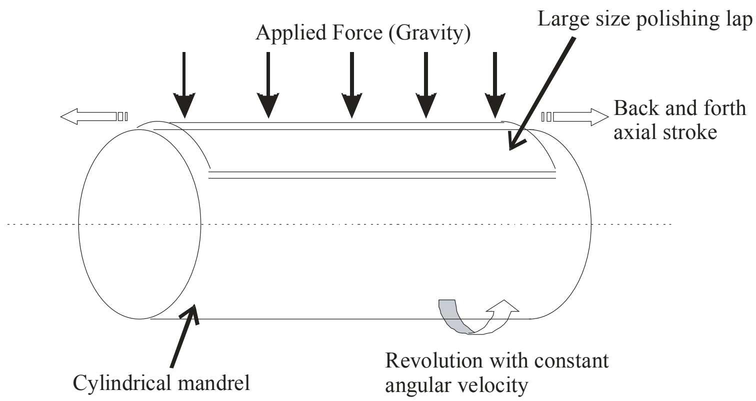


Fig. 1. Kinematics of a typical large area cylindrical polishing process

The lap itself is often made of aluminium and accurately machined closed to the desired overall shape. The pitch is poured on to the lap substrate is then pressed against a mandrel surface to be polished to generate the desired contour on the lap. The polishing lap is then grooved to facilitate the flow of polishing media over the lap surface as well as to provide areas that can act as reservoirs for the polishing medium and for the material removed from the surface of the substrate being polished. Each tile that is in contact with the surface of the mandrel is known as individual polishing tool. Therefore, a polishing lap can be considered as a collection of many individual polishing tools. The shape of the polishing tools depends on how the grooves have been cut. A polishing media is provided at the interface between the lap surface and the substrate to facilitate polishing. Figure 2 shows a schematic of a typical lap and surface in contact.

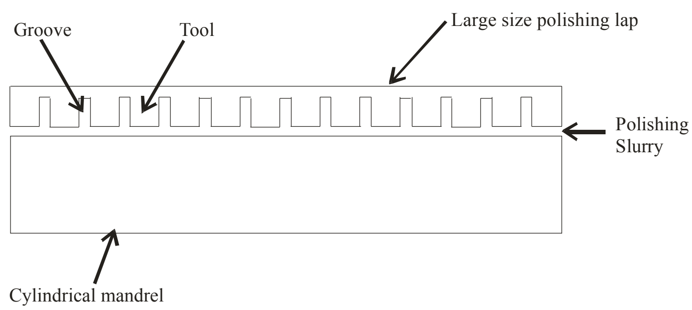


Fig. 2. Schematic of a typical polishing lap in contact with the surface to be polished

The production of mandrels has traditionally employed rigid tools to polish the surface. However, mid-frequency errors do often appear in the finished surface. These errors arise because of the inherent structure of the lap i.e. the shape and distribution of tools and grooves on the lap. The grooves may be closely spaced or randomly distributed, but in either case they leave areas of high slope error, thus generating waviness with spatial periods equal to their spacing. By polishing over these errors one can smooth them out, but new frequencies tend to develop simultaneously, and the finished surface does not improve significantly.

The residual errors will be higher if the surface to be polished is conic instead of a cylinder. Due to the conic shape of the optical surface, during the polishing strokes, the lap does not remain conformed to the surface. As a result, contact pressure between the tool and the workpiece is a dynamically changing function of time and position on the workpiece. This leads to enhance the already existing errors because of tool-groove distribution of the polishing lap. Such deviations are present in both the rotational as well as axial directions.

3. DESIGN CONSIDERATIONS OF POLISHING LAP

The main reason of performing the simulations is to find out the set of process parameters that that keeps the residual errors minimum. In order to control the residual errors, the material removed by the polisher as it travels over the surface has to be controlled. Material removal can be obtained by using Preston equation[4]

$$MR \propto p\, v\, t \quad (1)$$

where, p is the local pressure exerted by the tool on the workpiece, v is the local relative surface speed between the tool and workpiece and t is the dwell time of the tool with each element of the workpiece surface.

3.1 Effects of the process parameters

The controlling process parameters are the size and shape of the individual tool on the lap, tool-to-groove ratio, distribution of the tools over the lap surface, length of the axial stroke, and the axial and rotational speeds of the lap and the surface respectively. These parameters will eventually control the contour path of the individual tools over the surface. Under the assumption of constant pressure and the constant relative surface speed between the tool and the workpiece, the material removal depends only on the dwell position and time.

The aim of this study is to find out a set of parameters like tool size and shape, tool to groove ratio, linear velocity of the lap, rotational velocity of the workpiece and the stroke length that will remove the material uniformly over the entire surface. The effects of these process parameters on dwell are investigated in the present Section.

The lap is considered of having a collection of square tools as shown in Figure 3. The polishing simulations have been first performed on a cylindrical surface. The diameter of the cylinder is 108 mm and the length is 300 mm. To better understand the effects of the process parameters, an ideal surface i.e. the surface without any error, has been chosen. Once the shape, size of the tools, distribution of the tools and their dwell are optimized, the conical surface with actual surface deviations is considered in Section 3.3. A 325 mm long and 55 mm wide lap with small tool separated by a groove has been initially selected for simulation. The tool size is 25 mm and groove is of 5 mm.

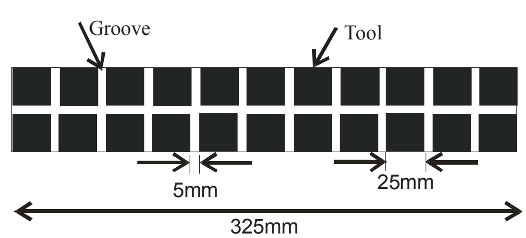


Fig. 3. Top view of the lap showing the distribution scheme of the tools.

The influence function represents the distribution of the material removal rate across the shape and size of the polishing tool. The knowledge of the influence function is essential for simulating the polishing process. It can be determined by performing a known set of polishing operation on a surface with known deviations. To start with the polishing calculations, an influence function with constant removal rate across the size and shape of a tool is considered. It removes the material uniformly under a tool as shown in Figure 4. The effects of slurry flow and tool (pitch) wear during polishing are not considered in the simulations.

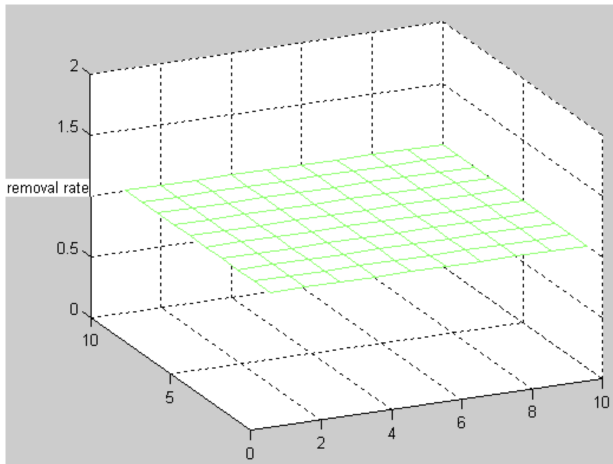


Fig. 4. An influence function with constant removal rate

3.1.1 *Relation between the Rotational speed and the stroke length of the lap*

In order to understand the frequency spectrum of the generated residual errors, the power spectral density (PSD) has been calculated. For the given circular and axial velocities, the rotational errors significantly depend on the stroke length of the lap. In one revolution of the mandrel, the polishing process generates periodic error of spatial wavelength (*SW*) in rotational direction. This can be given in the following equation:

$$SW_{rot} = \left(\frac{v_c}{v_a}\right) s + \varphi \tag{2}$$

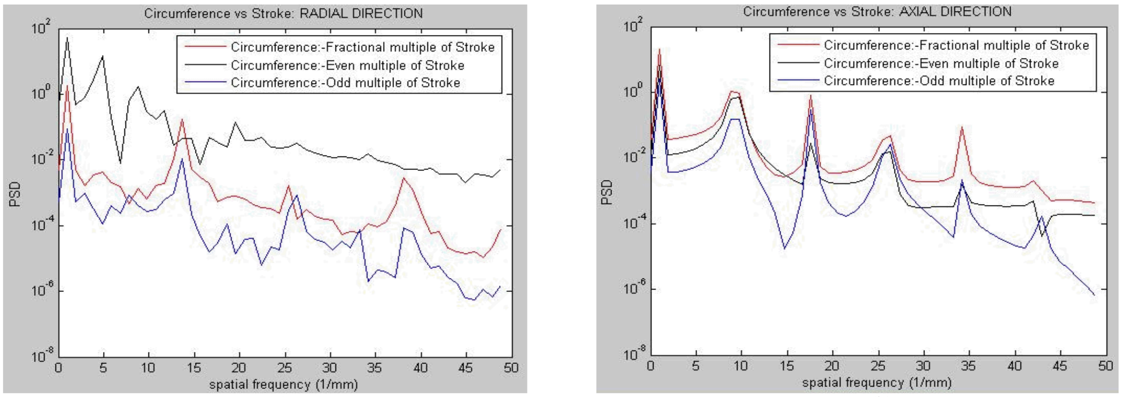
where, v_c, is the circular velocity, v_a, is the axial velocity , *s is* the stroke length, respectively φ is the phase of the undulations in the rotational direction.

If the circumference of the mandrel is an odd multiple of thus generated spatial wavelength, the undulations during the next revolution of the mandrel are out of phase with the previous one. This is the condition where the rotational errors would be the minimum after a long time of polishing. It leads to a restriction on the selection of stroke length by the following equation:

$$\frac{\pi D}{v_c} = n.\left(\frac{s}{v_l}\right) \tag{3}$$

where, *D* is the diameter of the mandrel and '*n'* is an odd integer.

A series of simulations are conducted by varying stroke length from 10 to 50 mm. The circumference of the chosen mandrel is 340 mm. The axial velocity of the lap is kept as 1 mm/sec. The tool distribution is as shown in Figure 3. Figure 5.a represents PSD distribution in radial direction for different stroke lengths. When stroke length is 34 mm, the undulations in every revolution of mandrel are in phase. In this case, the tool dwells with the same area of the work piece. For the stroke length of 20 mm, the circumference becomes odd multiple of the stroke length and the amplitude of rotational errors decreases significantly. In the axial direction (Figure 5.b) also there is a decrease in the amplitude in the case of stroke length of 20 mm, however, the frequency components remain the same.



(a) (b)

Fig. 5. a) Power Spectrum of the profile error in radial direction with varying stroke b) Power Spectrum of the profile error in axial direction with varying stroke

3.1.2 *Relation between the stroke length and the tool size*

A stroke length has been chosen that satisfies equ. 3. The tool size has been varied from 10 mm to 50 mm while keeping a constant groove of 5 mm. It is found that the amplitude of the power spectrum for mid spatial-frequency range errors is the minimum tool size becomes equal to size of stroke length. Figure 6 shows the power spectrum for when tool size is kept as 10, 20, 30 and 40 mm. For tool size of 20 mm, which was also the chosen stroke length, the amplitude of mid spatial-frequency errors is the minimum.

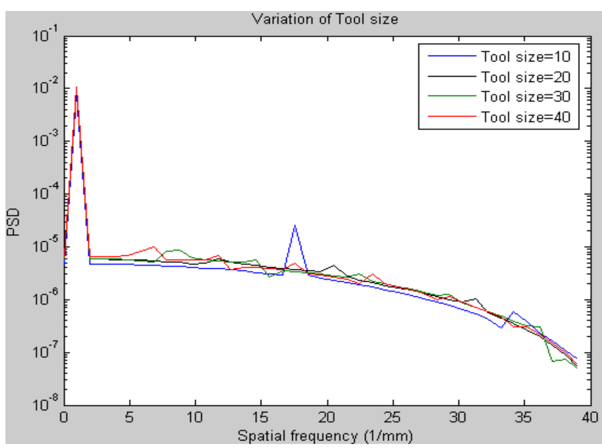


Fig. 6. Power Spectrum of the profile error in axial direction with varying tool size

3.1.3 *Effects of Tool-to-groove ratio and distribution of the tool over the lap surface*

Once the stroke length and the tool size are chosen, investigations of the influence of tool-to-groove ratio are made. As the tool size is already fixed, the groove size is varied from 5 mm up to the size of the tool. It is found that the selection of groove size equal to the tool size gives the best result when the distribution of tools on the lap is as illustrated in Figure 7. The equal tool and groove size case guarantees no overlap of dwell of two neighboring tools. The lap comprises two rows of the tools separated by a groove width which is the same as of the tool size. Such a shifted distribution of tools in two rows ensures that in one revolution of the mandrel, the whole surface has been scanned uniformly by the tools. Figure 8 compares PSD distribution of the polished surface when a tool distribution as Figure 3.

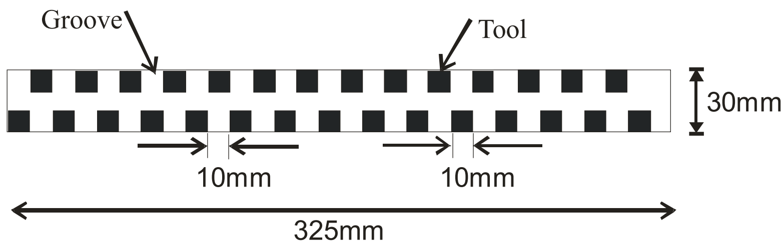


Fig. 7. Top view of the lap showing the distribution scheme of the tools.
The tools positions in two rows are shifted. The tool size is 10 mm.

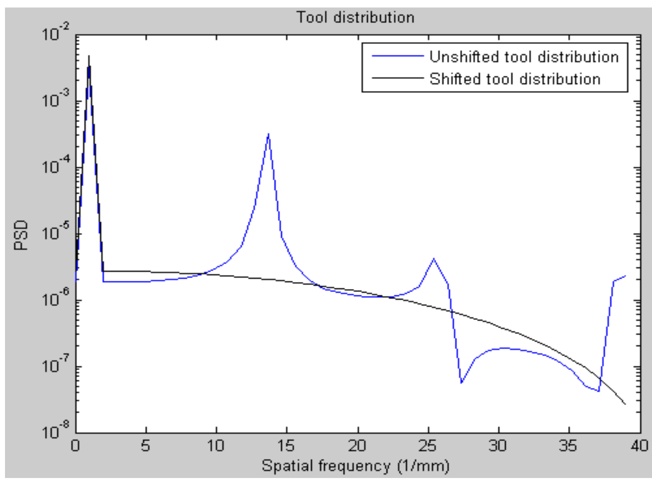


Fig. 8. Comparison of power spectrum of the profile errors

3.2 Material Removal in the presence of nonconformance error

In previous Section, the tool dwell and material removal is simulated under the assumption of constant pressure. Further, cylindrical surface was considered to keep the lap conformed to the surface during its axial motion. However, in the case of conic surfaces the lap does not remain conformed to the surface during the axial stroke. The nonconformance of the lap with surface introduces pressure variation under the individual tool. The pressure keeps on changing with lap stroke over the mandrel. The pressure on an individual tool can be calculated as a function of the tool position in azimuth as well as axial direction.

The polishing simulations have been performed when nonconformance errors have been added. The end diameters of the cone are 108 and 102 mm, and the length is 300 mm. The first step to compute polishing process is to find out the pressure experienced by lap in azimuthal direction at a given position of the stroke. Figure 9 shows the pressure variation under the lap during a stroke length of 10 mm. The lap is conformed at the middle of the stroke. It is clear that the more the width of the lap is, the more the pressure variation is in the azimuthal direction.

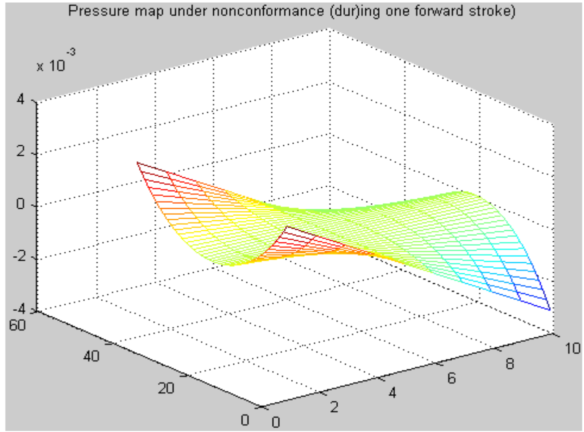
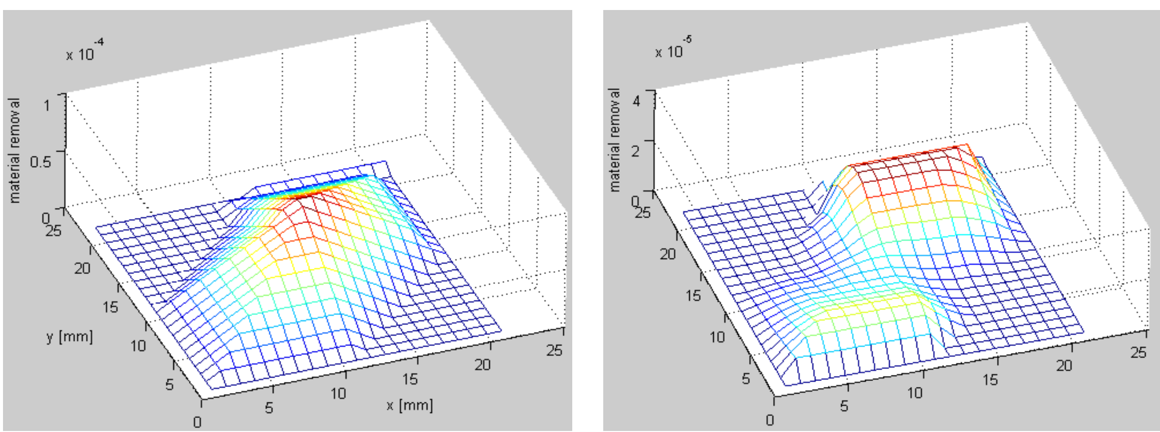


Fig. 9. Pressure variation under the lap during a stroke length of 10 mm

The removal rate distribution within an influence function depends on the pressure distribution caused due to the nonconformance. Material removal at a point is equal to the sum of the removal contributions from all points of the tool during its motion. Under the assumption of constant pressure and in the case of a cylindrical surface as chosen in Section 3.1, Figure 10.a depicts the material removal by an individual tool during its forward stroke of 10 mm. Figure 10.b shows the case when pressure variation, as per Figure 9, is experienced by the lap. It should be noted that the workpiece is also rotating at the same time with the same circular velocity as of the axial stroke.



(a) (b)

Fig. 10. Material removal by a square (10 mm x 10 mm) polishing tool a) under the assumption of constant pressure b) when pressure varies as per Figure 9 during the forward stroke.

3.3 Performance evaluation

Figure 11 shows a profile error on a mandrel which is polished without using optimized process parameters. There is mid spatial-frequency errors present in the axial profile. The assessment of the design considerations of polishing lap discussed in Section 3.1 is performed by simulating polishing routines on this profile. The aim is to remove the mid spatial-frequency errors in the profile. The surface is considered as rotationally symmetric. Once the amount of material to be removed is decided, the polishing simulations are allowed to run for the required time.

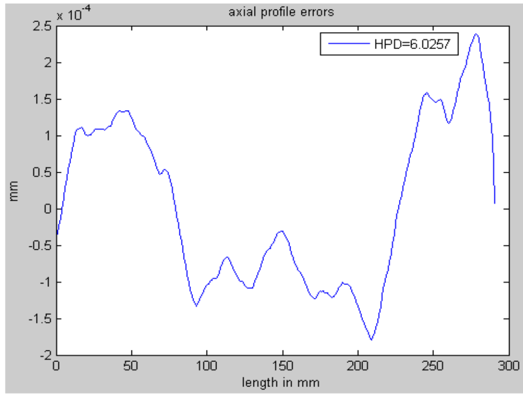
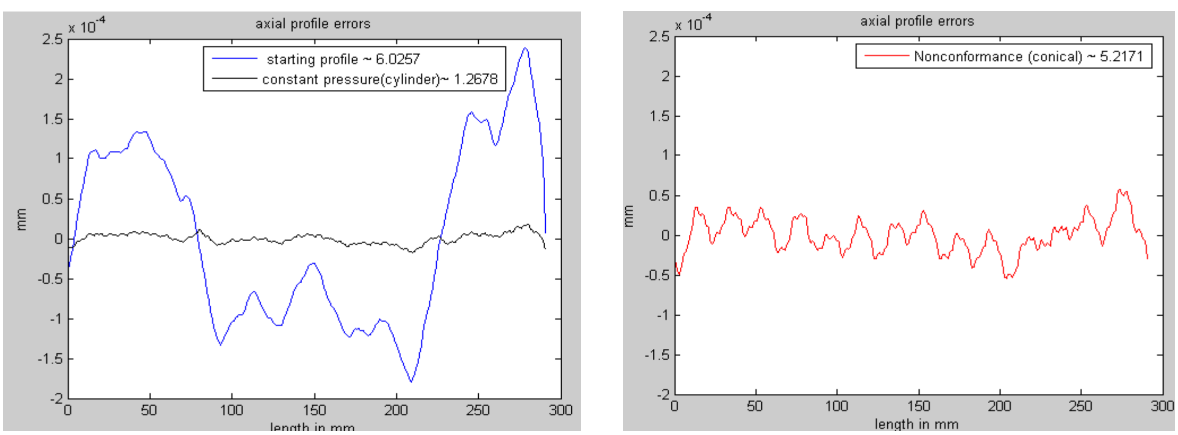


Fig. 11. Actual axial profile error on a mandrel polished without employing optimized process parameters

The performance is evaluated by calculating half power diameter. Figure 12 shows the achievable profiles for cylindrical surfaces where lap is fully conformed to the surface. The mid spatial-frequency component from the residual errors decreases drastically and the profile gives HPD as 1.26 arcsecs. When the profile is considered of a conic surface, where nonconformance errors are present due the dynamic pressure variation, mid spatial-frequency errors appear. Figure 12.b shows the residual error profile with HPD as 5.2171 arcsecs. This is because of the fact that due to the pressure variation as shown in Figure 9, in a forward stroke lap removes more material at the edges until half of the stroke. At the middle of the stroke, the lap conforms to the surface. In the second half of the stroke, lap starts removing more material from the center. This leaves an error on the surface of the wavelength equal to the tool size. It should be noted that the surface is also rotating and the tool path is diagonal on the surface as is clear from Figure 10.



(a) (b)

Fig. 12. a) Achievable axial profile errors after polishing simulations for cylindrical surfaces; a) where nonconformance errors are not present b) where nonconformance errors are present

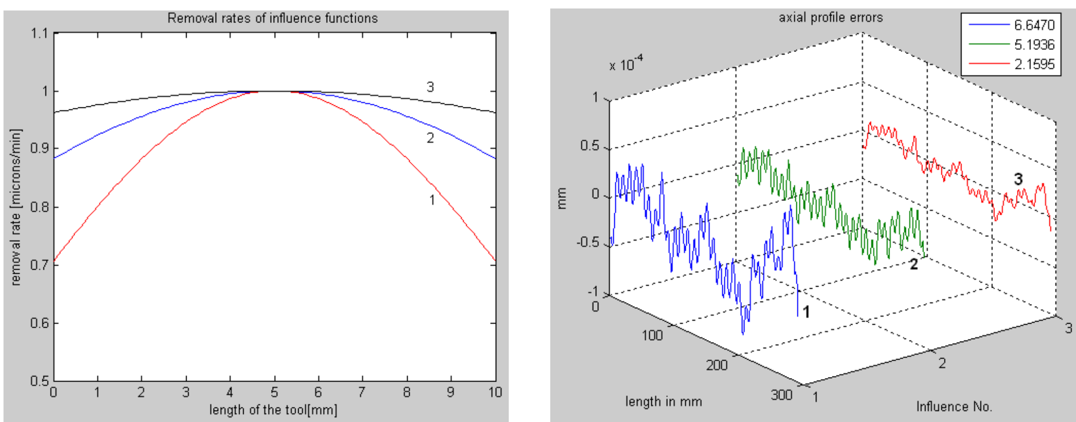
To circumvent the problem of continuous change in pressure distribution, a flexible tool is needed. The required flexibility depends on the conic parameters, tool geometry, influence function of the tool and their dwell. As the pressure variation is different along axial and azimuthal direction, the flexible tool requires different stiffness in the two directions. The design of such a flexible is under progress.

4. INFLUENCE FUNCTION

The influence function represents distribution of the material removal rate across the shape and size of the polishing tool. This Section presents a theoretical discussion on some characteristics of influence functions and their effects on the observed errors. The knowledge of the influence function is essential for simulating a polishing process. It can be determined by performing a known set of polishing operation on a surface with known deviations. The simulations presented in Section 3 were conducted under the assumption of constant influence function across the shape and size of the polishing tools. The influence functions are usually characterized by the maximum value in the data set and the amount of material that the polishing tool removes per unit time. Another characteristic of the influence function is its symmetry. Few simple influence functions have been considered and their effects on the polishing sequence have been discussed here.

4.1 Gaussian Influence Functions

The polishing simulations are performed using three different Gaussian shaped influence functions with different material removal capacity. Figure 13.a depicts the removal rates of these influence functions. All the three influence functions have the same removal rate at the center of the tool. However, it varies towards the edges. Figure 13.b shows the corresponding axial residual error profiles. HPD values suggest that the closer the influence function to a uniform removal, the better the achievable HPD is.

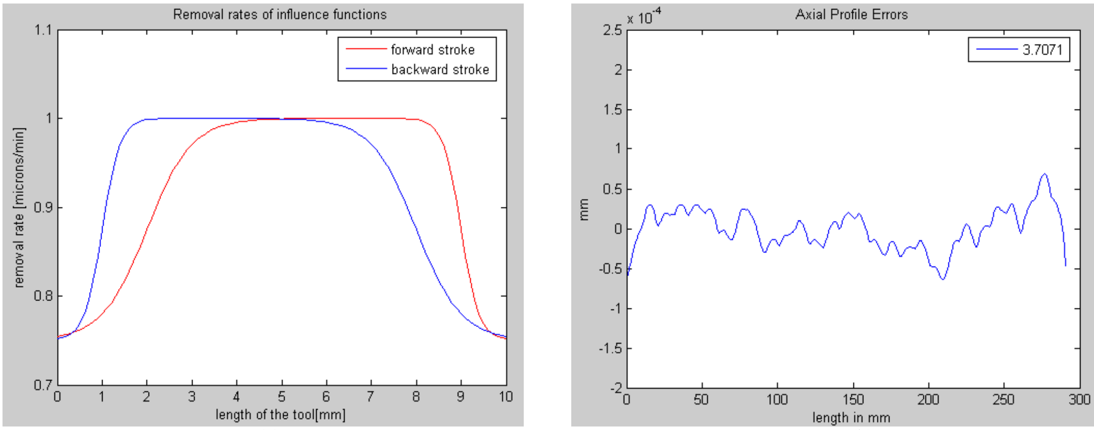


(a) (b)

Fig. 13. a) Influence functions with Gaussian shaped removal rates, b) Axial residual error profiles corresponding to influence functions

4.2 Asymmetric Influence Function

If the leading edge of a tool removes more material than the trailing edge, the influence function becomes asymmetric in shape. One such theoretical influence function is illustrated in Figure 14.a. Figure 14.b shows the corresponding axial residual error profiles. The HPD value becomes higher. This is because of the nonuniform removal rate across the size of the tool. Furthermore, the shape of the influence function becomes direction dependent and is different in forward and backward directions of the stroke. The study suggests that the influence function of a tool should be as symmetric as possible to obtain better quality surface.



(a) (b)

Fig. 14. a) Edge dependent Asymmetric influence function in forward and backward direction, b) Axial residual error profiles corresponding to the influence function

5. COMPUTER-CONTROLLED POLISHING MACHINE

The computer controlled polishing machine as shown in Figure 15 is designed and developed for deterministic and localized polishing cylindrical mandrels. Its motion and logical control software is developed. The control software will provide an option to have polisher motion with variable speed and applied pressure. In addition to that, at locations where the amount of material to be removed is more, small oscillations can also be applied. Some salient features of the machine are:

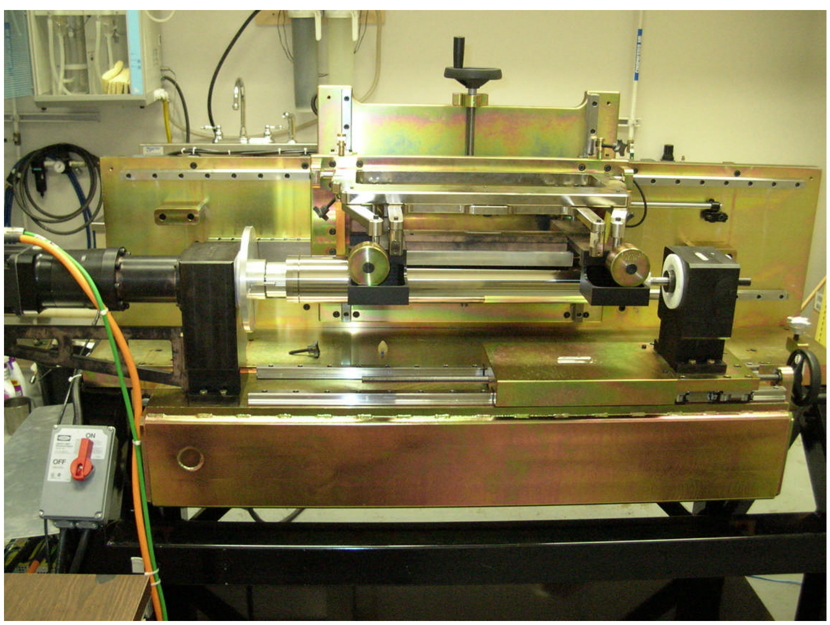


Fig. 15. Computer controlled polishing machine for deterministic and localized polishing of cylindrical electroless-Ni-phosphorous coated mandrels.

1. Accommodates specimen of length from 12 to 30 inches with diameter ranging from 1.5 to 12 inches.
2. In order to keep uniform pressure distribution on the optical surface, a floating lap is designed.
3. Applied pressure on the lap can be varied by addition of weights on the polishing pad.
4. Cog-free linear motor is employed to avoid vibration during polishing stroke.
5. Thermally insensitive linear scale feedback system with 10µm feedback resolution ensures the precise geometrical accuracies.
6. Straightness of 2.5 µm in axial motion.

6. CONCLUSIONS

Software is developed for cylindrical polishing that estimates the surface residual error under a given set of operating parameters and lap configuration. Using the developed software, investigations on computer-controlled polishing process for cylindrical optics are presented that helps finding out suitable polishing tool configurations, scanning paths, influence functions and operating parameters. The process is optimized by selecting a set of operating parameters that delivers the minimum residual error in mid spatial-frequency range.

Preliminary results of the simulation studies suggest that while designing the polishing lap, the stroke length, the tool size and the groove size should be kept equal. Furthermore, the distribution of tools on the lap should be such that within one revolution of the mandrel, the overlap of the dwells of any two neighboring tools is avoided. However, in the presence nonconformance errors, the residual mid-spatial frequency errors are still present. Design of a flexible tool appropriate stiffness in the two perpendicular directions is in progress. Further investigations on the tool distribution and their dwell overlap will be made once the actual influence function is determined.

The ability to simulate the polishing process is an important contribution to extend automation further and thus increase cost effectiveness. A computer controlled polishing machine is also developed and is ready for its first trials of polishing mandrels. It is expected that with the help of the simulations studies and the precision of the developed polishing machine, the mid-frequency errors on the surface of the mandrels will be reduced to bring the angular resolution of the final electroformed optics to 5 arcsec HPD or better.

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