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Mid-Spatial Frequency Error (PSD-2) of optics induced during CCOS and full-aperture polishing

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Mid-Spatial Frequency (MSF) Wavefront Error of optics divided into the PSD-1 and PSD-2 ranges plays an important role in the performance of high power laser systems. The present work focuses on the PSD-2 range in terms of short ripples which haven't been well studied in the literature. Characteristics and origins of these short ripples were detailed, whereafter small tool computer controlled polishing (CCP) and conventional full aperture polishing experiments were conducted on fused silica. It is revealed that PSD2 error is independent of the main process parameters including lap rotating rate and polishing pressure in continuous polishing and tool path pitch and crossfeed velocity in small tool CCP processes. Whereas the type of polishing lap has a decisive effect on PSD2 error of the optics. The pitch lap shows superiority in restraint of short ripples over polyurethane pad. By introducing diamond conditioner for dressing polyurethane pad, the PSD2 error has been greatly decreased.

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Keywords: PSD2 error, pitch lap, polyurethane pad, small tool CCP, continuous polishing

1 INTRODUCTION

The wavefront quality of the optics used in high power lasers is specified over a continuous range of spatial frequencies from 1×10^2 to 2.5×10^{-3} mm^{-1} [1]. This range of frequencies is divided into the four separate bands: surface figure (spatial periods within 400~33 mm), waviness-1 (i.e., PSD-1, 2.5~33 mm), waviness-2 (PSD-2, 0.12~2.5 mm) and surface roughness (0.01~0.12 mm). Figure determines most aspects of the main focal spot, waviness-1 effects the tails of the focal spot, while waviness-2 determines pinhole loading. Both of the waviness regions influence near-field modulation. Roughness contributes to pinhole loading and has been shown to play a role in filamentation [2]. There are two types of specification for the Mid-Spatial Frequency (MSF) PSD-1 and PSD-2 errors, a specification for the Rms value (<1.1 nm) over that range, and the other a not-to-exceed line for the power spectral density (PSD) as a function of spatial frequency [3]. Note that the integral of the measured PSD over the associated spatial frequency band is equivalent to the Rms value [1]. The entire optic is tested using a wavefront measurement when evaluating whether or not an optic meets PSD-1 spec. Much smaller regions (e.g., 10 x 10 mm) of the surfaces are sampled for evaluation of the PSD-2 spec [3, 4]. Considering the transmitted or reflected wavefront quality is specified respectively for optics that are transmitting or reflecting the laser beamline, the reflection optics required of reflected wavefront quality is considered and evaluated by the Rms value over the PSD-2 range in the present study.

It is well known that the PSD-1 error, in terms of long ripples (i.e., waves), is intensively correlative to CCP processes characterized by a small tool [5]. This error is mainly affected by the initial surface error distribution (spatial and frequency domain), the removal function characters (profile, removal efficiency and stability) and the adopted paths [6, 7]. A lot of attention has been paid to the optimizations of CCP process parameters and machine configurations [5],[7]–[9]. There are also some novel technologies and processes developed to restraint the long ripples in the PSD-1 range, such as pseudo-random tool paths and Vibe-finishing [10]–[12]. Although there are many researches conducted on characteristics of the long ripples of the PSD-1 region in the literature, little has been studied about the PSD-2 region. PSD-2 error represents short ripples across the optical surface with scale lengths between 0.12 and 2.5 mm. These short ripples generated on optics may be associated with those features in the fabrication process that with scale lengths lying in or close to 0.12~2.5 mm. The important factors maybe include the nature or properties of the lap material, surface characteristics of the lap/pad and the kinematics of the lap/pad and optic which intensively correlative to the polishing process.

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The present work is an attempt to understanding the generation and restraint of the short ripples of PSD-2 error. Experiments were carried out on fused silica flats with typical full-aperture polishing process (continuous polishing, CP) and small tool CCP processes. The extensively used pitch lap and polyurethane pad were employed in the conventional full-aperture polishing to evaluate the effect of lap material on PSD-2 error. For assessing the effect of texture of polyurethane pad, fused silica samples were polished on those pads with or without in-situ dressing by diamond conditioners. Furthermore, a series of polishing experiments were conducted by small tool CCP process with pitch laps of variable sizes and differing raster too-path pitches. PSD-2 error of these prepared fuse silica have been measured and analyzed.

2 PLISHING EXPERIMENTS AND PSD2 MEASUREMENT

Conventional full-aperture polishing experiments were conducted on a 36′ continuous polisher. Round fused silica samples (180 mm diameter × 20 mm thick) previously ground were polished using two typical laps, i.e., pitch lap and polyurethane pad (LP66 by Universal Photonics Inc.) to check the effect of the nature of lap material on PSD-2 error. All the samples were polished for 5 hours under the pressure of 0.4 psi. The platen speed was set to 20 rpm, noticing that the rotating rate of the optics was slightly lower than that of lap/pad. Small tool CCP process was conducted on an OP1000 CNC polishing system developed for Plano optics. A series of experiments were carried out with pitch lap to assess the effect of process parameters on the PSD-2 error. The round fused silica samples were previously ground and polished on the continuous polisher using a pitch lap. The raster tool path, one of the typical tool-paths extensively used by sub-aperture polishing processes was adopted. The most important process parameters including the lap size and tool-path pitch were considered, and all samples were removed a uniform depth of 0.3 μm in a polishing iteration.

An optical Surface Profiler was applied to the measurement of the reflected wavefront error over PSD2 range. The profiler uses filtered white light in a Michelson interferometer configuration. The measurements were taken in phase measuring mode with a 0.5x objective and a 0.5x magnification. This provided a field of view of 14.1 mm by 10.6 mm. A set of 5 radial-uniformly distributed samples were measured for each surface and the average Rms value over PSD2 range was obtained for evaluating the PSD2 error.

3 RESULTS AND ANALYSIS

3.1 Effect of process parameters on PSD2 error

Continuous polishing has been the mostly used full-aperture polishing process for flat optics. Process parameters determining the polishing performance mainly includes lap rotating rate, polishing pressure and so forth as described by the Preston equation [13]. Figure 1 shows PSD2 error of fused silica polished with pitch lap under differing lap rotating rate and polishing pressure. It is revealed that the Rms values over the PSD-2 range keeps at ~0.72 nm for variable polishing pressures. Also, at a certain polishing pressure of 0.4 psi, differing rotating speeds result in a stable PSD2 error of ~0.72 nm Rms. This may suggest that PSD2 error is independent of these mainly parameters but some other crucial factors. Table 1 shows the experimental configuration and results of the small tool CCP process. The Rms values over the PSD-2 range are observed to keep stable at ~0.73 nm Rms for variable pitch lap diameters and tool-path pitches. It may be concluded that effect of the main process parameters is negligible. Notable is that the PSD2 errors obtained in values are almost identical as obtained in the full-aperture polishing using the pitch laps.

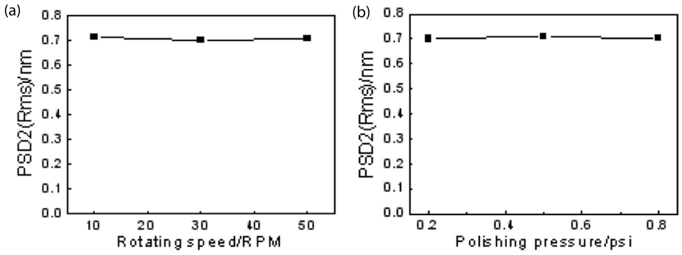
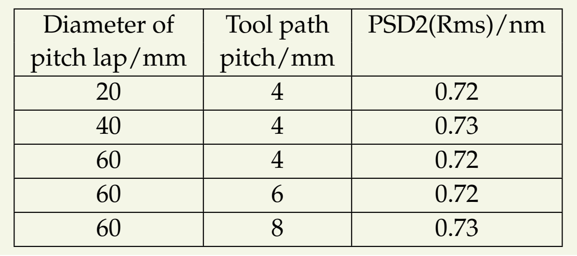


FIG. 1 PSD2 error of fused silica as a function of polishing pressure and rotating speed in continuous polishing. (a) Polishing pressure is set to 0.4 psi and (b) Rotating speed is set to 20 rpm.



Diameter of pitch lap/mm	Tool path pitch/mm	PSD2(Rms)/nm
20	4	0.72
40	4	0.73
60	4	0.72
60	6	0.72
60	8	0.73

TABLE 1 PSD2 error of fused silica by small tool CCP with variable parameters.

Generally, modern sub-aperture deterministic optical fabrication processes are more prone to ripple errors. The size of removal function and the pitch of tool path play an important role in the spatial frequency of the ripples or waves. In most small tool CCP processes, the polishing tools are usually manufactured by pitch or polyurethane pad. These tools generally have a diameter of tens of millimeters. Regular tool paths (commonly spiral or raster) with a pitch larger than several mm are adopt in consideration of efficiency. Features of these scales lie in the spatial frequency of long ripples, namely the PSD-1 range of 2.5~33 mm, rather than in the PSD2 range of 0.12~2.5 mm. Thus they don't have much impact on the PSD-2 error in terms of short ripples.

3.2 Effect of lap type on PSD2 error

Pitch lap and polyurethane pad, the two most used polishing laps, were determined herein. Figure 2 shows PSD-2 error of the optical surfaces polished with the pitch lap and polyurethane pad. The Rms value over PSD-2 range is ~0.71 nm for pitch lap polished surface, whereas the optic polished by pad has a much higher Rms value of ~1.62 nm. It can

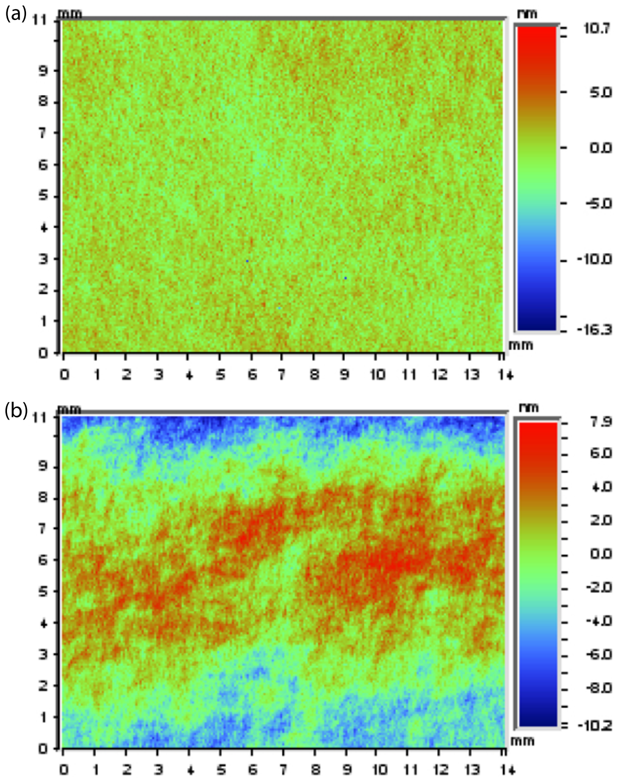


FIG. 2 PSD2 error of fused silica polished by (a) pitch lap and (b) polyurethane pad. (a) Rms=0.71 (b) Rms=1.62.

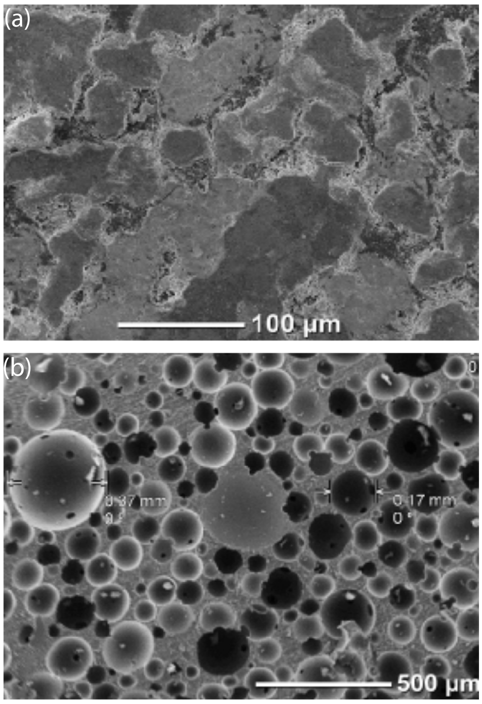


FIG. 3 SEM images showing surfaces of (a) pitch lap and (b) polyurethane pad.

be seen that the pitch polished surface is much smooth while the pad polished surface shows sub-mm & mm sized features, namely protrudes and conglomerations.

SEM image of the pitch lap shows a uniformly smooth structure of the surface (see Figure 3(a)). This smooth surface is beneficial to restraint of ripples or mid-frequency waves. Furthermore, the viscoelastic properties of pitch play an important role. Pitch acts as a highly viscous Newtonian fluid for long time scales – it undergoes shear motion that is proportional to the shear stress, so it flows to conform to the shape of the optic [14]. This fluidity at long time scales ensures smoothness of the whole lap surface when the lap strokes on the optic. Nevertheless, pitch will act like a solid for a short time period under stress [15]. It does not flow fast enough to conform to local short ripples that may exist on the optic when the pitch lap traverses the optic with a certain crossfeed velocity. As a result, these short ripples of PSD-2 range would be smoothed.

For the polyurethane pad, the texture and micro-structure of pad surface plays a vital rule in ripple generation. Generally, the pad surface has numerous independent pores separated by asperities [16]–[18]. Most of these isolated pores and asperities have a size of several tenths of mm (i.e., sub-mm), as shown in the SEM image of LP66 polyurethane pad produced by Universal Photonics Inc. (Figure 3(b)). As abrasive-occupied asperities yield material removal during polishing, it is prone to bringing features of their sub-mm scales on the optic.

During pad polishing, the surface of the workpiece is polished when the abrasive particles are pressed against the surface by the asperity of the pad. Under the force of the asperity, the particles are pushed against the surface, dragged along by the asperity at the relative velocity of the polishing pad with respect to the workpiece [19]. It is well known that material removal rate is markedly dependent of the pad surface roughness, which can be characterized by the roughness of the pad asperities. Pad asperities were glazed as a result of wear and plastic deformation by the workpiece during polishing, leading to roughness variation [20]. Thus diamond conditioning is continuously performed to break up the pad surface and restore the asperity roughness during polishing. The sub-mm sized asperity features especially the surface roughness may have a significant impact on the roughness and short waviness of the polished surface. For these reasons, we introduce dressing process in pad polishing to decrease pad surface roughness and may thus the SPD2 error of optics. To assess the effect of pad surface roughness on the PSD-2 error, fused silica flat was polished using a continuous polisher. The polyurethane pad fixed on the platen was in-situ conditioned by diamonds of variable sizes. The surface roughness of pad asperity was measured after each polishing iteration using surface roughness tester (Mitutoyo SJ-400). Considering the sub-mm sized pores and asperities, a sampling length of 0.08 mm was adopted as shown in Figure 4. The sampling location for roughness measurement should be carefully selected for ensuring that the stylus traverses on the asperity avoiding falling into deep pores during the measuring. A set of 5 randomly selected locations were measured and the average Rq value was obtained for evaluation of the surface roughness.

Figure 5 indicates that diamond dressing of polyurethane pad has a significant effect on pad roughness and PSD2 error of fused silica. The pad without being dressed yields a high PSD2 error ~1.68 nm Rms, but after dressed with 100 µm and 70 µm diamonds the Rms value decreases to ~1.55 and ~1.28 nm, respectively. Furthermore, dressing by 40 µm leads

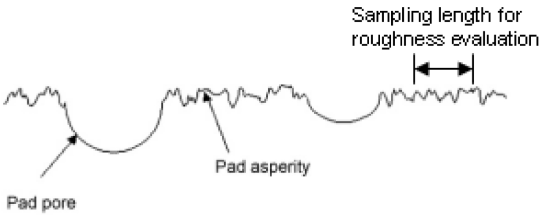


FIG. 4 Schematic of micro-structure of pad and roughness measuring.

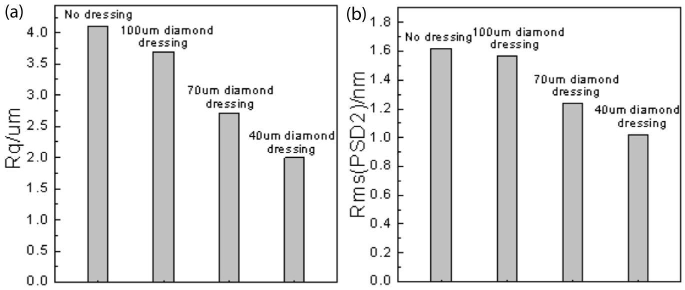


FIG. 5 Effect of diamond size on the pad roughness and the resultant PSD2 error of fused silica. (a) Roughness of polyurethane pad, (b) PSD-2 error (Rms) of the optical surfaces.

to a favorable Rms value of ~1.02 nm, which satisfies the specified eligible value 1.1 nm. Sampling surfaces polished by non-dressing pad, 100 μm, 70 μm and 40 μm diamond dressed pads are shown in Figure 6. It is obvious that the topography of the surface polished by non-dressing pad is much nonuniform with submicron & micron sized protrudes and conglomerations. These protrudes and conglomerations are lightly smoothed by using 100 μm and 70 μm diamond dressed pad, and further almost eliminated for 40 μm diamond dressed pad leading to an eligible Rms value of ~1.0 2 nm. Although dressing process wouldn't alter the size of pores and asperities on the pad surface, the effect of pad dressing on the pad surface roughness has been confirmed (see Figure 5(a)). Some other research has also revealed pad dressing has an impact on pad surface roughness and hence the material removal [21]. Conditioner with larger diamonds is deemed to increase the surface roughness of the asperities, which is most likely to promote the scraping process of the optic surface by the asperities. That is to say, small ripples on optic induced by these asperities are intensified. As a result, pad dressing using small diamonds would decrease the pad roughness and hence the PSD2 error of optics in terms of small ripples.

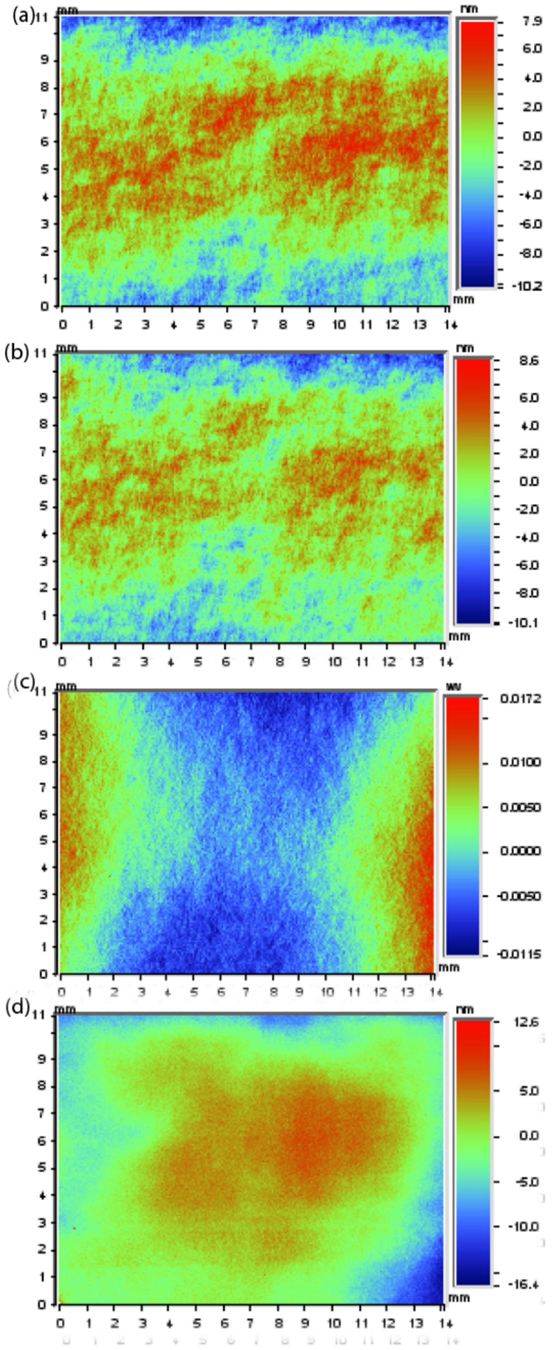


FIG. 6 Typical unfiltered raw data of surfaces polished by polyurethane pad with (a) no dressing, (b) 100 um diamond dressing, (c) 70 μm diamond dressing and (d) 40 μm diamond dressing.

4 CONCLUSION

Short ripples in the higher frequency region of MSF error was studied in terms of reflected wavefront of fused silica. The conventional full aperture polishing experiments revealed that the pitch lap shows significant advantage of restraining short ripples over polyurethane pad due to its fluidity. The sub-mm & mm sized pores and asperities on the polyurethane pad surface seem to be the origin of short ripples on the pad-polished optics. Pad dressing has a significant effect on PSD-2 error. Rms value over PSD-2 range has been decreased from 1.68 and 1.55nm with the newly-used and 100μm diamond dressed pad, respectively, to an eligible value of 1.02nm with the 40μm diamond dressed pad. This may be ascribed that fined diamond conditioner reduces surface roughness of the pad and thus diminishes scrape effect on optic surface by the pores and asperities. In the typical subaperture polishing processes, small tool CCP process exhibited superiority in restraint of short ripples as the lap size and tool-path pitch go completely beyond the spatial wavelengths of PSD-2 range. The study has provided some insights into the generation and restraint of short ripples on optics induced during polishing.

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