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Fundamentals of figure control and fracture-'free' finishing for high aspect ratio laser optics

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LDRD FINAL REPORT

Fundamentals of figure control and fracture-'free' finishing for high aspect ratio laser optics

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The high level objectives of the this work were to: 1) scientifically understand critical phenomena affecting the surface figure during full aperture finishing; 2) utilize these fundamentals to more deterministically control the surface figure during finishing; 3) successfully polish under rogue particle-'free' environments during polishing by understanding/preventing key sources of rogue particles.

During polishing of optical components, complex chemical and mechanical interactions occur between the workpiece, lap and slurry both at macroscopic scale lengths affecting the surface figure and at microscopic scale lengths affecting the roughness of the final workpiece. The final macroscopic surface figure of the workpiece is determined by the initial surface figure and the material removal that occurs on the workpiece during polishing. The spatial and temporal material removal is often described by the well-known Preston Equation as shown at the top of Fig. 1 where dh/dt is the instantaneous thickness removal rate as a function of position x,y on the workpiece at time t, k_p is the Preston coefficient, σ is the interface pressure distribution, and V_r is the average relative velocity between the workpiece and the lap [1-3]. The physical concepts or phenomena influencing the spatial and temporal material removal rate during polishing (shown schematically in Fig. 1) have been investigated in detail (both theoretically and experimentally) in this study. These include: (1) spatial and temporal variations in velocity and pressure; (2) differences between the applied pressure and the pressure distribution that the workpiece undergoes; and (3) friction effects [1-3]. In particular, the actual pressure distribution experienced by the workpiece is governed by a number of phenomena, including applied load distribution, elastic lap response, hydrodynamic effects, viscoelastic & viscoplastic lap response, moment forces, and workpiece-lap mismatch [2]. The workpiece-lap mismatch is the local height variation at the workpiece-lap interface (referred to as the gap) affecting the local pressure distribution (and hence material removal spatial distribution). In addition, we have characterized a number of phenomena can also influence the workpiece-lap mismatch (both temporally and spatially) including workpiece & lap shape, pad wear, workpiece bending, residual grinding stress, temperature, material deposit, and pad shrinkage [1,3].

At the microscopic level, the material removal is governed by the chemical or mechanical removal by individual polishing particles. The ensemble of removal from all the particles making contact with the workpiece is represented by the Preston Constant and friction coefficient as discussed above. Most approaches use the theory of Hertzian contact mechanics to describe the interactions (e.g., load and contact zone) between the individual slurry particles and the workpiece being polished. To quantitatively predict the resulting roughness, a number of phenomena have been recently investigated. In this study, we determined that the surface roughness is quantitatively correlated to the logarithmic slope of the distribution function for the largest particles at the exponential tail end of the particle size distribution (PSD) [4]. Also, the removal depth due to a single ceria particle in the plastic removal regime on fused silica glass was measured as ~1nm. Using the measured fraction of pad area making contact with workpiece surface, a quantitative model called the Ensemble Hertzian Gap (EHG) polishing model was formulated to estimate each particle's penetration, load, and contact zone. The EHG model was then extended to create simulated polished surfaces using the Monte Carlo method where each particle slides and removes material from the silica surface in random directions [4]. Fig. 2 shows a comparison between measured and simulated surface roughness using the EHG model.

The major steps in a typical optical fabrication process include shaping, grinding, full aperture polishing, and sometimes small tool polishing. With increasing demand for high quality optical components for imaging and laser systems, there have been significant advancements in optical fabrication over the last several decades; this is particularly true with shaping & grinding and small tool polishing steps of the optical fabrication process. However, the intermediate step of the finishing process, full aperture polishing (spindle or continuous polishers using pad or pitch laps) still lacks high determinism, typically requiring skilled opticians to carry out multiple, often long, iterative cycles with multiple process changes to achieve to the desired surface. A new, novel, patented system and method of polishing called Convergent Polishing has been developed representing a paradigm change in how full aperture finishing has been historically conducted. The basic strategy behind Convergent Polishing is to eliminate or minimize the undesirable causes of non-uniform spatial material removal (described above), either through novel engineered polisher design or by process control, such that removal is driven only by the workpiece-lap mismatch due to workpiece shape [1-3,5].

As a result, the Convergent Polishing protocol and system is a compilation of a number of developed technologies allowing for convergence in surface figure, high material removal rate, and high surface quality (low scratch densities, low surface roughness) through minimization of rogue particles [1-3;5-9]. The key enabling technologies are a result of first developing an understanding of phenomena outlined in Fig. 1. These technologies include:

1) A novel shaped septum: compensates for non-uniform pad wear, improves temperature uniformity, improves slurry distribution, and reduces viscoelastic pad edge effects [3,5]

2) Bulk etching: allows for more rapid removal of sub-surface damage and reduces the amount of material to be removed from the workpiece during polishing

3) Pitch Button Blocking: allows for blocking a high aspect ratio workpiece preventing it from bending during blocking and polishing with low risk of scratching the opposing workpiece surface[8]

4) Radial stroke: results in improved material removal spatial time averaging during polishing, preventing high frequency ripples that can occur on a workpiece surface[3]

5) Balanced 3-body wear of workpiece, septum and lap: provides a desired, stable shape of the lap and hence a more stable convergent point of the workpiece[3]

6) Hermetically sealed high humidity polishing chamber: prevents entry of external rogue particles and prevents formation of dried slurry agglomerates which are common sources of workpiece scratching; also reduces chance of pad drying and permanently deforming the lap shape[5]

7) Engineered filtration system: improves and maintains a desired slurry particle size distribution improving surface roughness and reducing probability of scratch formation; this includes features of fluorinated piping, minimized dead zones, and controlled flow velocities preventing slurry settling, agglomeration, and contamination[5]

8) Chemical slurry stabilization: reduces the number and size of agglomerates in the slurry without sacrificing material removal rate using surfactants that follow a novel 'Charged Micelle Halo' chemical mechanism [6-7]

9) In-Situ ultrasonic pad treatment: allows for removing slurry and glass product deposits from lap surface which helps maintain high material removal rates and minimizes mid-range spatial scale length workpiece shape degradation due to preferential material deposit [5]

A photo of the Convergent Polishing system is shown in Fig. 3 [5,9]. The process has been demonstrated on various size (round, square, low & high aspect ratio) glass workpieces for fabricating flats and spheres. For example, the process enables fabricating square fused silica flat workpieces (26 x 26 x 2.5 cm^3) repeatedly from an unpolished, ground surface to a $\lambda/2$ peak-to-valley surface figure after polishing 4 hours per surface (i.e., a finished optic in a single shift) (see Fig. 3). The practical impact is that high quality optical components (windows, lenses, mirror substrates, etc.) can be fabricated more rapidly, more repeatedly, with higher yield, with less metrology, with less labor, and less costly labor. Hence, Convergent Polishing offers such optical components to be manufactured with higher throughput with less upfront investment resulting in lower unit costs. Recently, the Convergent Polishing system and process was awarded an R&D100 award.

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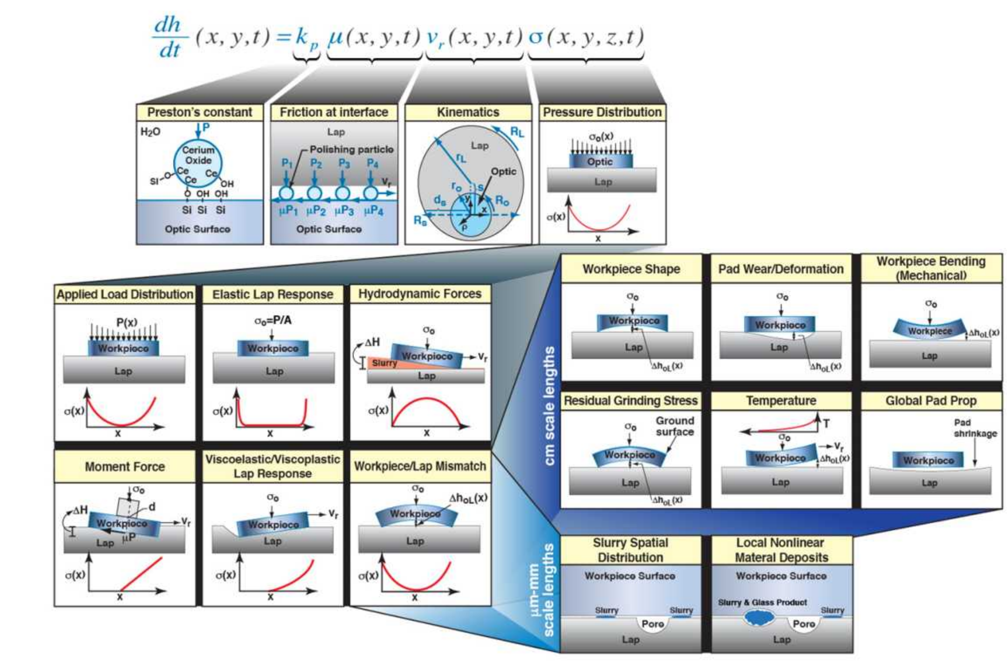
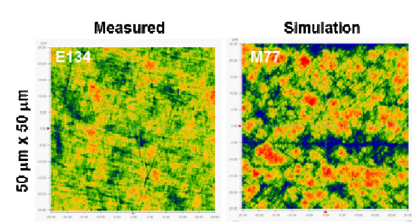


Figure 1. Schematic illustration of the phenomena affecting spatial and temporal material removal during polishing (after [6]).



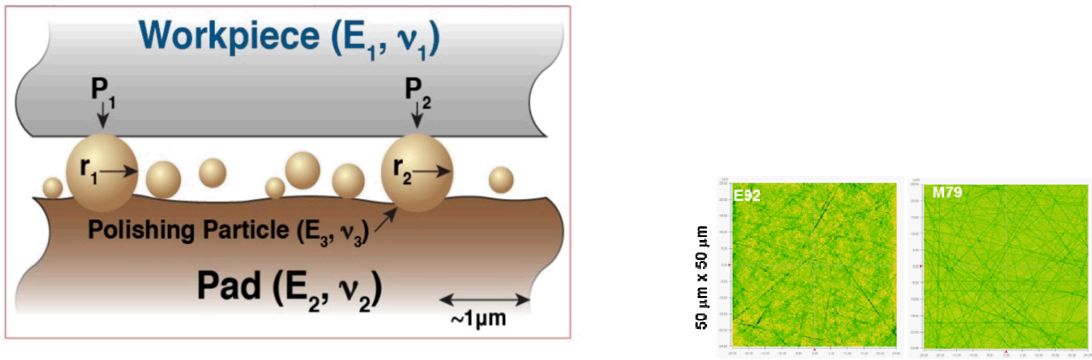


Figure 2. (left) Schematic illustration of the Ensemble Hertzian Gap model describing the removal by individual loaded particles during polishing [8]; (right) comparison of measured (AFM) and simulated surface roughness of workpieces polished with slurries with two different particle size distributions (Unstabilized Hastilite PO slurry (top); Stabilized Hastilite PO slurry (bottom)) [8].

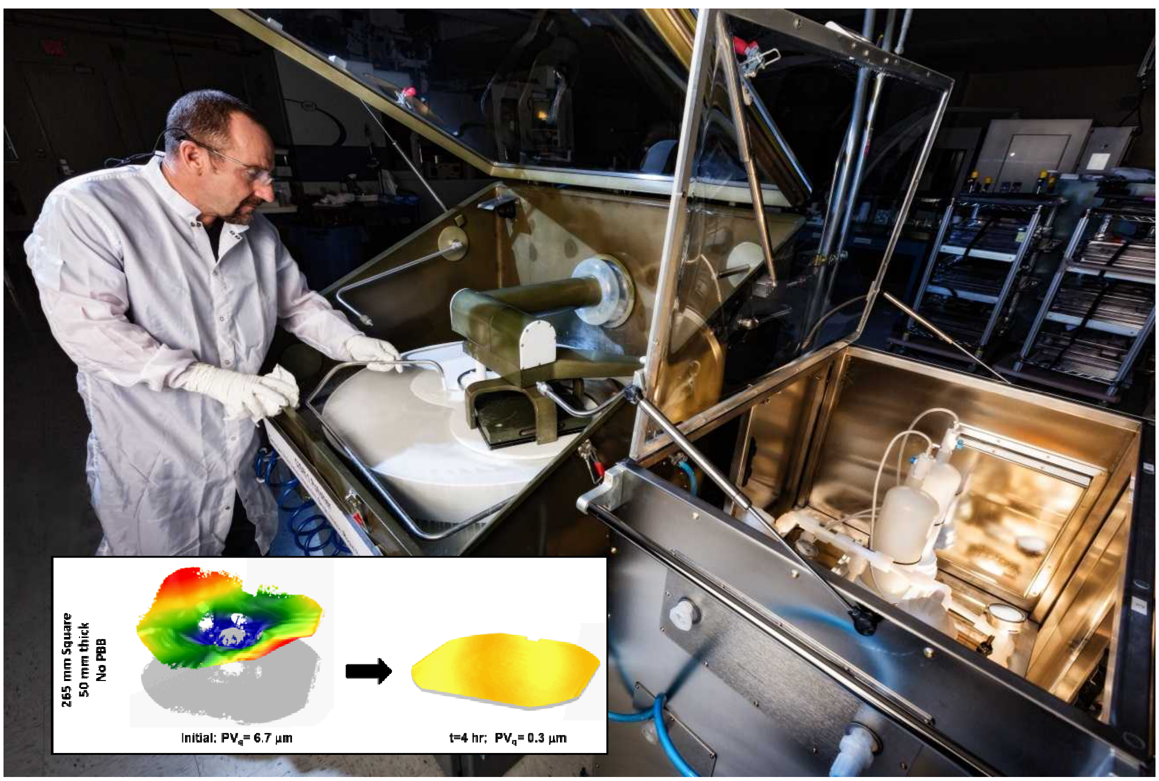


Figure 3. Photo of Convergent Polisher (called CISR-1) using for finishing 26.5 cm square workpiece; (Insert) Surface figure before and after polishing using Convergent Polishing method [2,5,9].