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Pad polishing for rapid production of large flats

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ABSTRACT

Pad polishing is an efficient technique for polishing-out a ground surface and reaching a figure better than one wave, ready for completion with less than an hour on a planetary polisher. Recent work has shown success on 350 mm square parts; current work involves scaling the process to 1.4 meter diameter. For the 350 mm square piece of BK-7, removal was one micrometer every 10 minutes. Polishing-out from a 5 micrometer grind took less than 3 hours, to a surface smoothness of one nm rms. Other tests verified that the pad leaves no unusual subsurface damage. Following completion on a pitch planetary polisher, surface finish is the same as obtained for conventional processing.

Unlike pitch, the pad retains its surface figure, producing a uniform result when used on a production basis. Coupled with the speed of production and low capital cost of overarm machines, it provides a cost-effective approach.

Keywords: optical polishing, optical fabrication, rapid fabrication, pad polishing

1. DESCRIPTION OF PAD POLISHING

Pad polishing is a simple modification of conventional optical polishing. The significant difference is the substitution of a polyurethane pad for the usual pitch. The substitution of pad for pitch makes it easy to use high speeds and high forces, giving a high removal rate without concern for flow in the pitch. No pressing tools are needed. Once a lap has been brought to a proper surface shape, it can be used for months.

The process still follows Preston's law (ref 1) -- the removal rate is proportional to pressure and speed. For given abrasive and glass types, the coefficient of removal is approximately the same for pad use as for pitch polishing. The advantages of conventional polishing are significant and are retained with pad polishing. These advantages include: 1. the process uses inexpensive machinery; 2. the process naturally tends to a smooth flat or spherical surface; 3. nanometer changes in surface figure can be achieved with easily made changes in machine parameters; 4. the process is applicable over a wide range of sizes; and 5. it is effective for manufacture of single items or for production of volume quantities.

Because the pad retains its shape, errors in curvature or spherical aberration can be corrected with predictable changes in machine parameters, leading to a nearly deterministic process. We hope to quantify these factors in the near future for some polishing conditions; but since the work to date is a small effort done in a small shop, the rate of progress is limited.

We use pad polishing because it is the quickest and best way to bring a ground surface to a good polished-out surface (1/2 to 1 wave figure). Most of our work has been in the size range of 100 to 300 mm, round or square. One of the advantages of using the pad has been the relative ease of maintaining figure quality out to the corners of square pieces. Our work has only been on flat or nearly-flat surfaces. It is hoped that we can extend this to spherical work in the near future.

A surface finish of about one nanometer rms is typical. It can probably be made better -- the process has not been optimized in terms of surface roughness. With this smoothness and a figure better than one wave, final figuring can be done with pitch in a very short time.

The pad polishing removes the subsurface damage from grinding and produces no harmful damage even at high speeds and pressures. One of the applications for our parts is for phase plates in the laser-fusion programs. After polishing, these are etched to obtain the desired half-wave phase patterns. Any residual subsurface damage shows clearly when the plates are etched. No such damage is detected for parts produced with the pad followed by pitch.

2. WORK ON SMALL AND MID-SIZE OPTICS

Our use of pad polishing began as one of several approaches to reduce the expected cost of a KrF laser fusion system. The system designs called for several thousand square meters of flat optics of moderate size (100 to 400 mm square). Pad polishing had been used extensively for electronic parts. The question to be answered was whether it could meet surface figure and smoothness requirements for precision optics.

A positive result was easily obtained. Figure 1 shows the lap, its use on a small machine, and a diamond-button tool used for surfacing the lap. A slight convex radius, about 70 meters, is desirable for producing flats. The piece was 150 mm square. The resulting figure and smoothness are shown in Figure 2. The relative ease of obtaining the desired figure and the favorable performance at the corners provided encouragement to continue development of the process.

In part because of the improved smoothness that can be obtained with a pitch polish, it became apparent that the most effective process involved traditional grinding through several grit sizes, followed by pad polishing. The pad polishing is used to remove surface damage from grinding, to obtain a polished-out surface, and to obtain a figure of better than one wave. A fairly brief run on a pitch planetary polisher then produced the desired figure and smoothness (0.02 wave rms figure; < 0.5 nm roughness). On a production basis, optics could then be produced with a total machine time of only 240 minutes, using a schedule as in figure 3. These results and the implication that optics for a laser fusion system could be produced in a remarkably short time were reported previously (ref 3) but not published.

A later requirement to produce optics for the Nike laser at the Naval Research Laboratory gave an opportunity to test the process in somewhat of a production mode (ref 4). The optics were 100 mm square with a 6 meter convex surface. By proper shaping of the pad, and by placing a concave curvature on the planetary polisher, the parts were produced with a 0.02 wave rms figure on approximately the 240-minute schedule.

3. SCALING TO 350 mm SQUARE; AND MEASUREMENT OF REMOVAL RATES

In response to a need for larger optics for the National Ignition Facility (NIF), an effort was begun to scale the process to larger sizes. This was begun with a 350 mm square slab of BK-7, 50 mm thick. It was polished face down on a pad on a 750 mm diameter machine. Scaling was successful, as a surface figure quality of near 1/2 wave was easily obtained. In preparation for work at larger sizes, the slab was ground and the process repeated on a larger, 2-meter, machine. The machine and the resulting interferogram are shown in figure 4.

The rates of material removal were then measured throughout a grinding and polishing cycle. The material removed was measured by measuring the thickness of the piece near each of the four corners. The measurement was made with a mechanical probe having an electronic readout with a least count of 50 microinches (1-1/4 μm , or 2 waves at the standard HeNe wavelength). The measurement was made by placing the glass on a granite table, with two edges near a corner in contact with two reference bars. The probe was mounted on the table and positioned so as to measure about 20 mm in from the corner. Calibration was checked by using a standard machine-shop reference block. The measurements were usually repeatable at the 50 microinch level.

THE PROCESS HISTORY AND AMOUNTS REMOVED WERE AS FOLLOWS:

1. The previously polished surface was ground with 20 μm compound for 20 minutes. All grinding was done with a cast iron lap. Removal: 47 μm . Surface figure: concave, 1 μm sag over 200 mm diameter (measured with a spherometer).

2. The grind was repeated. Removal: 52 μm . This indicates that the grinding rate with this coarse material doesn't vary as a function of the finish of the starting surface.
3. Grind, 9 μm grit, 20 minutes. Removal: 28 μm . Surface figure: concave, 2 μm . The machine stroke was then changed slightly to reduce the surface curvature.
4. Repeat the previous grind. Removal: 21 μm . As might be expected, the removal rate decreased slightly as the initial roughness was removed. Surface figure: 1 μm .
5. Grind, 5 μm grit, 20 minutes. Removal: 18 μm . Figure: still 1 μm sag over the 200 mm diameter of the spherometer.
6. Polish on the polyurethane pad for 60 minutes. All polishing was done on the pad with PO Hastilite, a standard polishing compound. Removal: 9.5 μm .
7. Repeat the polish, again 60 minutes. Removal: 5.1 μm . As expected, the rate decreases as the initial roughness is polished off. Surface figure: 4 waves concave, including 2.5 waves of spherical aberration. Surface roughness: 1.0 nm.
8. Repeat the polish, 60 minutes. Removal: 6.0 μm . Then change the stroke to correct the concave figure.
9. Repeat the polish, 60 minutes. Removal: 12 μm . The figure was much over-corrected, going very strongly convex. The removal was large; but mostly at the measured corners, accounting for the large apparent removal. Roughness: 0.7 nm. This is very smooth, typical of a pitch-polished surface, and indicates that the piece is very thoroughly polished-out, with subsurface damage probably eliminated. The stroke was then changed again.
10. Repeat the polish, 60 minutes. Removal: 2.5 μm . Figure improving.
11. Repeat the polish, 60 minutes. Removal: 3.8 μm . Figure 0.2 wave rms, 0.8 wave peak-to-valley.

The removal rate during polishing was quite constant at about 6 μm , or 10 waves, per hour. The apparent variation was a result of a serious figure change during which more was removed from the corners on one cycle, and more from the center on the following cycle.

The figure was very responsive to changes in stroke and offset. After the over-correction, the figure was quickly brought back. The responsiveness, which seemed to be greater than when using pitch laps, may be a result of the unvarying shape of the pad. It does not change shape as the workpiece changes, providing a more constant removal function.

Based on 6 μm per hour, it should take about 2.5 hours to polish through a depth equal to 3 times the grinding grit size and thus to remove subsurface damage. After one hour the roughness was 1.0 nm rms, a level that may have been adequate to switch to final pitch polishing, if desired. After three hours it was certainly completely polished-out. These times are longer than on earlier smaller work. The earlier work was done at much faster speeds and pressures that were not within the range of our 750 mm diameter machine.

Calculation of the coefficient for Preston's equation is somewhat difficult, but an estimate can be obtained. The pressure on the piece was 5.6 kPa (0.7 psi). The rotation rate of the table was 22 rpm; the offset of the piece from table center was 180 mm. The rotation of the piece was close to synchronized, meaning that the piece rotated about once for each rotation of the table. In that condition, the average velocity is equal to the table rotation rate times the offset. This gives a velocity of 0.4 m/s. Substituting into the equation (removal rate) = $K * P * V$, where removal rate is 1.7 nm/s (6 μm per hour), P is 5.6 kPa, and V is 0.4 m/s gives a coefficient of $K = 0.7 * 10^{-12} \text{ Pa}^{-1}$. This is approximately the coefficient for BK-7 with conventional polishing.

4. SCALING TO 1.4 m DIAMETER

Following the successful polishing of the 350 mm square slab, work was begun on the next sizes of interest: 0.9 m diameter debris shields for the Nova laser, and approximately 0.4 by 0.8 m rectangular slabs to simulate the laser slabs for NIF. Preliminary polishing work, and development of fixturing for handling, mounting, and test has begun. The debris shields have the added difficulty that they are thin, only 10 mm; but the figure requirement is also loose, needing a little better than one wave on each surface, a quality that should be achievable on the pad without requiring final pitch polishing. For the rectangular slabs it was decided to polish two at once in an almost square pattern.

Work was begun using a 2-meter machine. A 1.5-meter diameter plate was mounted on the table and ground flat. It was then covered with the pad, requiring a joint down the center, and the pieces were polished face down, as had been done for smaller sizes. Again, as with smaller sizes, symmetrical figure errors such as power and spherical aberration responded to adjustments of stroke and offset. Further work on these pieces awaits available time and an improvement in test capability.

The work was interrupted by the desire to explore the polishing of a 1.4 meter diameter fused silica piece. A brief but somewhat intense effort was undertaken. After some quick development of handling and polishing fixtures the polishing was begun. In this case, the piece was mounted on felt on a slightly undersized plate, allowing a small space at the edges for handling. The piece was restrained from lateral motion by three lateral supports at the neutral plane of the piece. A one-meter tool covered by the pad material was then used for the polishing. The arrangement is shown in figures 5 and 6.

Preliminary work showed that polishing-out could be done in two or three hours. As expected, it took longer in this case where the tool was smaller than the work, and significantly longer than on the small machines where larger speeds and pressures were used. The process worked as expected. At this larger size and somewhat slower rate, each grinding step would show the irregularity left by the preceding step, demonstrating that at this size careful grinding is of critical importance for obtaining a good figure, as well as for minimizing time to polish. After only three hours of polishing, the figure was quite good. Testing over several regions with the 450 mm test plate showed little power or irregularity, less than two fringes over the test plate.

The brief effort was then ended on a successful note. The ability to polish quickly to a reasonably good figure was demonstrated and the figure was responding to machine adjustments in a normal fashion. The prospects for reaching our usual polished-out quality of better than one wave are favorable.

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FIGURES

Figure 1a: Pad

Figure 1b. In use on machine.

Figure 1c. Diamond button tool for shaping pad.

Photo: R David Little

Figure 5: Piece mounted on polishing machine.

Photo: R David Little

Figure 6: Fused silica being pad-polished.

Figure 2: Surface smoothness and figure produced on 175mm square fused silica.

Figure 3: Fabrication time on machine for flat optics.

Photo: R David Little

Figure 4: 350mm square BK-7 slab being pad-polished on large machine, and resulting figure.