LA-UR-79-2057

TITLE: POLISHING LARGE NaCl WINDOWS ON A CONTINUOUS POLISHER

AUTHOR(S): Ray Williamson

SUBMITTED TO: LASL Conference on Optics '79
Los Alamos, NM
May 23-25, 1979

MASTER

University of California

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POLISHING LARGE NaCl WINDOWS ON A CONTINUOUS POLISHER*

Ray Williamson
University of California
Los Alamos Scientific Laboratory
Los Alamos, NM 87545

Abstract

The Helios and Antares CO₂ fusion laser systems incorporate numerous large sodium chloride windows. These must be refinished periodically, making necessary a consistent and predictable polishing capability. A continuous polisher (or annular lap) which might fulfill this requirement was purchased and a process development program was undertaken at Kirtland's Developmental Optical Facility.

Large NaCl windows had not been polished on this type of machine. The machine has proven itself capable of producing $\lambda/16$ figures at 633 nm (HeNe) with extremely smooth surfaces on glass.¹ Since then, we have been working exclusively on NaCl optics. Due to different polishing parameters between NaCl and glass, and the slight solubility of the pitch in the slurry, this phase presents new problems.

The work on glass will be reviewed. Results on NaCl to date will be reported. The potential of this type of machine relative to prisms, thin and irregularly shaped optics will be discussed.

Introduction

The Los Alamos Scientific Laboratory (LASL) is engaged in a research program in laser fusion using short-pulse CO₂ lasers operating at 10.6 μ m. Helios is presently operating in the 10-kJ, 20-TW regime. Antares, presently under construction, is expected to produce 100 kJ and up to 200 TW at its completion in 1983.

The wavelength of 10.6 μ m and the extreme power of the beams limits the choice of materials for optical components. Copper-surfaced metal reflectors and forged polycrystalline NaCl windows will be used exclusively in the high-power regions of these lasers. The limitations imposed by NaCl windows have, in fact, largely determined the optical design of Antares.²

NaCl, easily fogged and scratched, with a coefficient of thermal expansion eight times that of BK-7, is one of the more demanding of optical fabrication challenges. These windows are expected to degrade and damage occasionally. Refinishing these windows will make a considerable impact on our vendor's capacity. If saturable gas absorbers are used to suppress parasitics, the stock of windows in Antares alone would reach 200, 18-inch windows.

LASL's Laser Division has initiated a NaCl polishing development program to improve figure and polishing efficiency. This program was carried out at the Kirtland Air Force Base Developmental Optical Facility, operated for the Air Force by International Laser Systems.

The Process in Overview

The continuous polisher (CP) utilizes an annular pitch lap which is impressed to a plane by running under a heavy plane conditioning plate once each revolution (0.5-1 rpm). The table which carries this pitch is very stiff, and isolated from bearing imperfections. The NaCl windows are held in any of three work-rings and are "planed off" by the pitch passing underneath.

The table rotation, and all temperatures and rates are held constant. Ideally, a NaCl window in thermal equilibrium in the machine enclosure is placed in the work-ring and left alone long enough to polish the surface and again guarantee thermal equilibrium, and is then removed without perturbing the rest of the system. Deviations from flatness of the pitch lap occur slowly, and adjusting the radial offset of the conditioner (no more than every several days) restores flatness in a predictable manner.

*Work performed under the auspices of the U.S. Department of Energy

Choice of Machine Type

Although large NaCl had never been finished on a continuous polisher (CP), its potential advantages over the overarm type made an eloquent case. During a single stroke of an overarm machine, the relative velocity of work piece to lap changes continually. The pressure distribution across the piece also changes continually in complex ways. Heat of polishing changes with relative velocities and pressures. After testing, the piece must be replaced on a lap which has idled for some time. A CP can hold all these parameters constant, avoid overhang, and testing may be done on a monitor piece without perturbing the system. Additionally, three pieces may be polished simultaneously on one CP. (These machines are variously known as ring laps, planetaries, Lapmaster R, and annular laps. Here I am using the term CP for continuous polisher.)

Description of the LASL 60" CP

A ring bearing, for support directly under the conditioner, was chosen. Yet, even a precision lapped bearing can have 1-mil runout -- hardly an optical tolerance. If the table is rigidly connected through the bearing to a stiff support structure, the table is bent around local defects. I decided to make the support and table stiff, but the connection between them elastic.

In our machine, the support is a cylinder sitting on three feet, lapped on top (Fig. 1). The bearing is 40 inches, precision lapped. The table is 8-in.-thick mild steel, also lapped. In between are twenty, 2-in. O-rings of 3/16-in. cross section. The rest of the machine is flexibly coupled to the cylinder base by horizontal plate, and is supported by its own set of feet around the perimeter. During acceptance testing, an electronic spherometer with precision of 2 μ in. over its 10-in. ring stayed dead true as it rode around with the table, even when a large man jumped on the table 90° away from it.

We chose a steel table because it was cheaper than aluminum, less fragile than granite, and at 8 inches, which was easily obtainable in steel, it would be very stiff. Also, granite's thermal conductivity is very poor, making it possible to sustain a thermal gradient for a full day's operation. The thermal decay time of an 8-in.-thick steel table is 45 minutes to 10% of initial gradient. That is, coincidentally, the same response time as a 3-in.-thick NaCl window.

In order to avoid hidden moments, which could unpredictably and adversely affect the distribution of load onto the lap, the conditioner is edge-driven by polyurethane wheels as near to the table as practical, and is otherwise unconstrained.

An ammeter to indicate load on the conditioner drive has proven useful as a diagnostic of lap fit and to save fuses during startup with a new lap. Controls include individual rotation rates with tachometers for the table, conditioner, and each work station. Panic shut-off buttons are provided on all sides of the CP.

The large thermal coefficient of expansion of NaCl warrants careful accounting of all heat sources. The machine is well designed in this respect, with the table drive enclosed in an insulated box which is ducted outside, the electronics ducted, the underside of the table insulated, and the conditioner and work-ring drives located a meter above the table. Polishing heat is a function of slurry temperature, fit, and rotation rate. Fit should be good and will change very slowly. Rotation rates were specified to maintain any setting with <1% variation. And a recirculating slurry temperature control may be set within 0.03°C.

Program Plan

We were to be running a brand new machine, the first of its design. We planned to polish larger NaCl than had been attempted on a CP. There was not much information on recipes for NaCl on a CP. A careful program plan was necessary. Thus we planned to give this new machine a shake-down cruise with glass and aqueous ceria to determine any quirks and limitations of the machine and the workability of our techniques before attempting NaCl. The program had distinct phases and milestones:

1. Install, enclose, and clean machine.
2. Set up to polish borosilicate glasses using Gucolz 73 pitch, Rare Earth 65, and water.
3. Find neutral (zero figure change) conditioner placement with synchronous rotation rates.
4. Note differences between work stations at neutral.
5. Characterize effects of each control parameter independently. These are temperature, conditioner offset, and asynchronous rotation rates.

6. Refine techniques to have confidence of producing $\lambda/8$ (HeNe) on pyrex, consistently.
7. Develop pitch and slurry recipes for polycrystalline NaCl (using a smaller machine concurrent with above).
8. Shut down machine and outfit for NaCl.
9. Reconfirm control parameters with new recipe.
10. Polish NaCl and refine recipe.
11. Achieve $\lambda/2$ (HeNe) on 12-in. NaCl with $\lambda/2$ roll-off over 1 inch, 60-40 surface quality.

Set Up

The CP was installed in a room in the Kirtland Air Force Base Developmental Optical Facility (DOF). The table bearing's support cylinder was leveled, and the feet at the perimeter of the superstructure were jacked to match. It was enclosed in a windowed, HEPA filtered modular clean room. The optician can thus monitor the CP, operate other machinery, intercept visitors and answer their questions without incurring traffic in the enclosure.

The table was painted with xylene and pitch to form a binding layer. With stainless steel pitch cams inside and outside and the table heated by heat lamps overnight, a 2-cm layer of Gugalz 73 was poured, 40 kg in all. The pitch was heated to a thin liquid before pouring, and the table was rotated at 0.5 rpm until it set, so the layer was quite uniform. Blowerdrones applied to the surface helped eliminate bubbles.

The new pitch lap was then face-cut with a standard lathe tool on a set of ways provided over the annulus.

The lap refacing or trimming tool is a weak spot in the operation. Ideally, the cutting tool (a standard lathe bit) is translated slowly on ways provided over the table as the table is rotated at 5 rpm. The ways are not straight, and the adjustments not repeatable. Thus, refacing is an iterative process. If a parallel flat is placed on the freshly cut pitch surface and a 90° reference mirror is mounted thereon, an autocollimator may be set up to check the deviations from plane. Readings are taken across a diameter of the lap on both sides of the central hole as the flat and reference mirror are moved. A mal-adjusted cut will produce a conical lap. This may be remedied by pivoting the ways about one end. Imperfection of the ways will show up as deviations from the cone (or plane) and may be remedied by appropriate vertical adjustments of the cutting tool during its slow traverse.

This method is limited in practice to approximately 1 arcminute, and is used only on a brand-new lap. Once the lap has been run a better method of refacing can be utilized: a dial gauge is mounted below the cutting tool and a set of readings are taken from the smooth (and by now fairly flat) lap which give the correcting factors to duplicate this shape. Then the correcting factors are applied to a vertical screw at the cutting tool during the refacing cut. This has to be done once every five weeks, at an average.

The lap was then faceted in equilateral triangles, 10 cm base to apex, 1/4 cm deep. This pattern was chosen to avoid the astigmatism generated by square or diamond cuts, and assure equal size and depth cuts across every zone, thus guaranteeing uniform lap compliance.

To avoid extreme lap compliance at the inner and outer boundaries of the annulus, a ledge is cut one facet depth down to define the inner edge, and the stainless steel cam used to pour the lap is replaced at the outer edge one facet depth down as a barrier to pitch flow.

The facets cut into the pitch lap are critical. Their purpose is twofold -- as drainage and distribution channels for the polishing slurry, and as empty spaces to take up the plastic flow of the pitch and allow it to conform to the desired shape. With facets too few and too shallow the lap will not respond to correcting forces and the NaCl, deprived of slurry, will not polish well. With facets too numerous and deep, the lap compliance will be too high and the lap will mush and plow, leading the conditioner.

Lap compliance is proportional to the mobility (reciprocal viscosity) of the pitch, at the running temperature, the width of the facet, and the square of the facet edge area.⁵ Thus, lap compliance may be quadrupled by (1) making the facets twice as deep, or (2) making the facets four times as numerous, or (3) raising the running temperature about 30°C. Using Gugalz 73 pitch at 76°F, square or triangular facets of 2 in. width by 1/8 in. depth to 4 in. width by 1/4 in. depth have given good control. Small scratches, 1/32 in. deep every 1/2 in., are put in with a tree saw blade scraped across the surface. These scratches, recut every day, have proved essential when using the pitch surface with 4 in.

and larger facets. Recently, paraffin has been used as a thin surface layer. Hopefully, the small scratches will not be necessary with 2 in. square facets and paraffin or beeswax coating, but this is not yet demonstrated.

Paraffin, beeswax, and other types of wax are inert to the triacetin which attacks Guggiz pitch, and are softer. A wax coating promises finer surface scratch quality on the NaCl. But wax does not flow like pitch. Therefore, the wax coating must be painted on (not) over facets which are deep enough not to be blocked by the coating, and must then be faced off with the lap trimming tool to a thickness of between 5 and 50 mils before polishing.

The first attempt to run the machine with aqueous ceria slurry caused high loading on the conditioner drive, chattering, and blown fuses. Disconnecting the conditioner drive for three hours was sufficient to run in the new lap. The drive wheels were found to be out of parallel, and binding caused more blown fuses. After realignment, the compression of the wheel under load was found to cause windup relative to the drive wheel not under load. Replacement of the unloading drive wheel with a nylon wheel of slightly smaller diameter solved this problem.

Machine Characterization with Glass

After identifying the neutral offset of the conditioner, we checked the rate of figure change as depurified from neutral by running at the new offset for 2 hrs and returning to neutral to stabilize. Conditioner offset proved to be a very smooth and predictable control parameter (see Fig. 2). Of course, the relative scales will change with different pitch, facets, and temperature.

Within an accuracy of $\lambda/20$ (HeNe) over a 12-in. pyrex monitor, there are no differences between the work stations. Figure control remains good from 25° to 27° C, although a lap left warm over a weekend will drift, and its facets will need more frequent maintenance. Conditioner rotation rate has little effect on figure, enabling us to use asynchronous running to break astigmatism. Asynchronous running of work station rings causes slight convexity.

With the achievement of $\lambda/16$ full aperture on 12-in. pyrex, and $\lambda/16$ on a 10 to 1 aspect 19-in. pyrex, the shakedown was considered complete. A 12 in. by 16 in. window of an unknown crown glass was polished to $\lambda/2$ to within $1/2$ in. of the corners.

A recipe is offered (Fig. 3), which may be considered a starting point for workers attempting borosilicate glasses.

Work with NaCl

Experimentation on various pitches and slurries has been primarily done on a small overarm machine, and has not always produced the same ranking of merits as on the CP. A 1:1 mixture of triacetin and monoacetin was found to be best on the overarm but produced disastrous (20 fringe) rolled edge and frosty surfaces when used on the CP. A paraffin coating produced the best surface ever on the overarm with brushed linc A and triacetin. As of this writing, we cannot say whether a paraffin surface is best on the CP. Guggiz 73 has by no means been certified as the ideal lap material for NaCl. Its cleanliness is good and viscosity is appropriate for the types of faceting we have employed, but further experimentation is warranted.

Although good for NaCl, neither triacetin nor monoacetin produce any appreciable polishing action on Cervit 9, of which our conditioner was made. It has retained the good plane polished onto it during work with glass, albeit with a severe orange-peel surface, for several month's operation. Consideration should be given to repolishing the conditioner with an aqueous ceria slurry every few months, perhaps just before refacing the lap.

The usual operation of CP's assumes that the conditioner will be polished as the annular lap flows so that they become complementary spherical sections. A conditioner which does not respond to the lap was not initially considered an acceptable situation. While some thought had been given to facing the conditioner with a layer of some appropriate material, we decided to first see what kind of control was possible with the naked Cervit conditioner.

If the flat surface of the conditioner produced during work with glass could be preserved (and it appeared that it could for a number of months) we would produce a different family of lap configurations.

It is usual for the conditioner to be polished by the lap while the conditioner impresses its shape into the lap, thus forming mating sections of spheres. But our conditioner stays flat. When offset to the inside of the annulus, pitch flow is increased at the inside of the annulus and the lap becomes concave, as in the usual model. The conditioner contacts the lap around the conditioner's circumference, and it lists inward toward the center of the table. Thus the circumference of the conditioner determines a sphere which mates the lap. The difference between this and the customary model is that the rest of the conditioner does not mate. (It may also list into the rotation of the table, generating a toroid. The drive wheels have been placed very low to minimize this tendency.) NaCl will be polished to mate this sphere, and should come off as a convex sphere with good surface quality due to good overall contact.

If flatness is approached from the convex side (concave spherical lap) a good fit and adequate diagnosis can be maintained.

Now consider the case where the conditioner is offset to the outside of the annulus. Again, the pitch flows differentially. The annulus becomes convex, or center up. But a convex spherical lap, if it could be produced, would contact the plane conditioner only at its center. High pressure at this zone would cause pitch flow there and nowhere else, until the pitch conformed to some shape which spreads the load over all radial zones of the annulus. This shape can only be a cone with vertex up, in line contact across the plane conditioner face.

Line contact would likely scratch the NaCl, and would give little indication of the extremity of the lap cone.

The NaCl, which is worked on by the lap, will not duplicate the plane of the conditioner. The reason for this may not be apparent. Imagine the abrasive on the outside of a shallow cone coming slowly up toward contact with the NaCl. When the pitch is a grain diameter away from the NaCl, contact occurs. As the pitch rises farther, the grain digs into the NaCl. Then the pitch, holding the grain, retreats and contact is broken. It should be clear that this contact sweeps some length, and can thus be called a "fat line".

Now if the lap is a cone, and the rotation of lap and workpiece are synchronous, then the pressure-velocity-duration product, or work done on the NaCl, should be the same for every zone in contact across the meridian of the cone. But this contact line has some width E . The amount of material to be worked on in each radial zone of the NaCl is proportional to r , the distance from the center of the NaCl. Thus the removal rate integrated around a zone or is proportional to E/r . Clearly, the center has the most work done on it, suffers more heat input, and consequently expands into the lap causing greater pressure and more material removal. A status quo will again be reached, but not at thermal equilibrium. There will still be line contact and scratching at status quo, but further, the NaCl will attain a concave figure when thermal equilibrium is restored. Increasing the rotation rate of the NaCl will increase the work done on the outer zones of the NaCl, but will still not avoid line contact at status quo and therefore not avoid scratching.

Monocetatin was incompatible with polishing NaCl on the CP. Crazed, foggy NaCl with rolled-down edges was the norm. Incompatibility with our slurry system was partly to blame. The slower polishing rate of the CP also allowed chemical etching to dominate or the CP when monocetatin was used.

Pure triacetin did produce surfaces of high luster and smooth figure on the CP, although scratching is a problem. Scratching was lessened by elevating the temperature to 25°C, slowing rotation to 1/2 rpm, and avoiding the slurry system altogether. A single, light brushfeed in the morning lasts all day and produces the best surfaces.

The softening of the pitch was manageable with a single brush-feeding. The lap is scrubbed with soap and water every evening to remove the triacetin. Since we avoid the recirculating slurry system, contamination of the machine with water is no problem.

The persistence of a few No. 80-100 scratches has been blamed on loose pitch canicles. We tried a pitch lap with paraffin face on the overarm machine, and got the best surfaces and least domain relief to date. An additional advantage is that paraffin is not damaged by triacetin. For two days after brushing hot paraffin on the CP lap, we saw unique and original figures, but as the lap pressed in, the figures returned to normal.

Figures of 1X to X/4 (FeNe) over 11-in. and 18-in. polycrystalline NaCl have been regularly obtained. The figures are smooth, showing no domain relief and no high spatial frequencies. The figure and surface quality are usually good to 1 cm from the edge.

A fortuitous characteristic of NaCl is that its high rate of thermal diffusivity and fast polishing rate imply rapid equilibrium and rapid correction of initial irregularities. Thus a pre-polished NaCl window can be completely figured in <2 hrs per side.

Additional Applications for CP

While the CP is limited to flatwork or long radius spheres, and change of radius is an operation requiring up to two weeks' shutdown, there are offsetting advantages to the production shop grappling with difficult flatwork. Its ability to work many pieces under constant conditions and its insensitivity to geometry of the workpiece make it ideally suited to some of the most difficult work.

Thin pieces need not be blocked. The constancy of temperature and polishing rate and avoidance of overhang make it the machine of choice for parts of high aspect ratio. Bags filled with shot or water can uniformly increase polishing pressure, if necessary.

Strong wedges can reach thermal equilibrium and avoid the asymmetry of figure characteristic of faster polishing under loads. An identical wedge taped back-to-back with the workpiece will provide even gravity loading.

Noncircular parts or parts with holes can be treated much like standard circular parts. No surrounds or plugs are necessary.

Prisms are particularly interesting. Several may be optically contacted to angle bars and worked simultaneously to the same reference. In fact, the ends of the angle bar can be the restraint points inside the work-ring, thus avoiding any moving contact with the prism other than the lap face.

Conclusions

Our 60-inch CP has completed a shakedown operation in which it has polished borosilicate glasses consistently well. Figures of $\lambda/15$ at 563 nm over a 12-inch piece, and $\lambda/5$ over a 19-inch piece have been obtained with no evidence of edge roll. Surface quality is typically better than 10-2. It is insensitive to oddly shaped parts, and shows potential towards the most challenging flatwork applications -- wedges, parts with holes, prisms, thin parts, etc.

Polycrystalline NaCl has been regularly polished to within $\lambda/4$ out to within 1 cm of the edge of 12 in. and 16 in. pieces. High frequency zones and grain relief are absent. Figure is achieved in a few hours. Three surfaces may be run simultaneously, so that two windows per day is conservative for a production run. Surface quality is a remaining bug, and damage threshold has not yet been tested.

Conditioner offset is a sufficient and predictable parameter for control of optical figure when using an edge-wheel driven conditioner. Although Cervit[®] does not respond to the triacetin and Linde A, refacing the conditioner has not proved necessary to maintain figure control when the lap is not allowed to go convex.

Acknowledgements

I would like to express my appreciation to Bob McGillicuddy and John Bender of ILS at Kirtland, who have handled the daily operation of the machine and were responsible for many of the discoveries which made this program successful; to Tom Walsh of Strasbaugh for his translation of my specifications into a workable machine; to Norm Brown of LLL for his extensive characterization of CP techniques and many helpful discussions; to Stan Truitt of Design Optics for stimulating discussions; and to Walt Reichelt of LASL, Granam Flint of ILS, and Jerry Charlton of USAF Kirtland for clearing the path to a cooperative inter-agency effort.

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Fig. 1. Table support and bearing, 60-inch CP.

Fig. 2. Figure change rate vs conditioner offset.

GUGGLZ #73 PITCH, 40 kg, MELTED SLOWLY OVERNIGHT AND POURED ONTO HEATED TABLE.
 20" PITCH WIDTH, LEDGE ON INSIDE AND DAM ON OUTSIDE 1 1/4" BELOW POLISHING SURFACE.
 EQUILATERAL TRIANGULAR FACETS, 4" BASE TO APEX, GROOVES 1 1/4" DEEP BY 45°.
 (PARTS SMALLER THAN 6" MAY REQUIRE SMALLER FACETS.)
 RARE EARTH 55, 1 1/2 GALLON IN 10 GALLONS WATER.
 1 RPM ON ALL ROTATIONS, ±1/2 RPM. KEEP ALL SYNCHRONIZED AND CONSTANT.
 ROUGHEN PITCH FACE EVERY OTHER DAY WITH HACKSAW BLADE.
 MAKE 10 MIL FACING OUT EVERY OTHER WEEK.
 TRIM FACETS AS NECESSARY.
 MAINTAIN 72°F ±1° SLURRY, 74°F ±1° AIR. SLURRY CHANGE 0.05° 10 MINUTES.
 COVER PARTS WITH INSULATING FOAM.
 LET PARTS SOAK IN POLISHING ROOM TEMPERATURE BEFORE RUNNING.
 LET PARTS RUN UNINTERRUPTED AT LEAST AN HOUR MORE THAN THEIR THERMALIZING TIME.

Fig. 3. A recipe for borosilicate glass on Strasbaugh's 60-inch CP.