Bound-Abrasive Polishers for Optical Glass

Optical finishing of glass consists of generating (grinding) and polishing stages. In grinding, brittle fracture is performed on a workpiece using a series of two or three bound-abrasive grinding tools. These tools are composed of diamonds in a metal or resin matrix. The generating process starts with a coarse (~60 μm) diamond tool, and concludes with a medium (~15 μm) and (optional) a fine (~3 μm) tool. Reliable, repeatable, deterministic microgrinding with ring tools using Opticam CNC machining platforms developed at the Center for Optics Manufacturing (COM) produces spherical surfaces with rms surface microroughness of ~10 nm,[1] subsurface damage with a depth of less than 3 μm,[2] and peak-to-valley (p–v) surface shape errors less than 0.3 μm (λ/2).[3] On blanks to 100 mm in diameter, the process takes minutes per surface. Bound-diamond-abrasive ring tool generating has been adopted by many optics manufacturing companies in the U.S. as part of a modern finishing strategy when small quantities of prototype lenses are required with rapid turnaround. No specialized tooling is required, and diamond ring tools may be obtained from many suppliers.[4]

Determinism in the polishing stage of optics manufacturing continues to be elusive. As it is traditionally employed, polishing is a full-contact operation between a polishing lap, or *polisher*, and the workpiece. An aqueous abrasive slurry is introduced to the contact zone to hydrate the glass surface, and removal of the softened near-surface layer is achieved by chemomechanical effects and plastic scratching.[5] Loose-abrasive slurries are typically composed of cerium oxide (CeO_2) in water.[6] The polisher is composed of pitch or polyurethane on a cast iron backing plate.[7] Pitch is the preferred lapping surface for achieving subnanometer surface finishes on glass with high precision. Although much progress has been made in understanding slurry fluid chemistry,[8] slurry-workpiece electrostatics,[6] and the interaction among polishing abrasive, the polisher, and the part,[5] the conventional pitch polishing process continues to be heavily iterative in nature. Pitch is chemically unstable and loses organic volatiles with time.[9] Its compliance is also very sensitive to temperature.[10] As a reference template against which the part is continuously worked, a pitch lap must be frequently checked and corrected. The polishing step is the main bottleneck to reducing finishing time in rapid prototyping. Sub-aperture processing technologies using small pitch-surfaced tools[11] or ion beams[12,13] have found utility in selected applications. A newly developed process, magnetorheological finishing, has demonstrated the ability to rapidly and automatically polish out flats, concave/convex spheres, or aspheres on a magnetic fluid lap with no specialized tooling.[14]

An optics manufacturing company invests in excess of $200K to purchase, install, and operate a CNC diamond ring tool generating machine that can produce a *nearly* finished glass part. There is strong economic incentive to devise ways that would permit the use of such a machine to complete the finishing process by polishing out the part, thereby eliminating the need for any further processing steps and machines. One possible approach is to develop a bound-abrasive ring tool polisher, resident in the on-board automatic tool changer, to act as a final surface-finishing tool. The use of a bound-abrasive polisher has several potential advantages: Confinement of the abrasive in a binder enables finishing to be performed on a CNC machine platform. Large quantities of loose abrasives would destroy the guideways of the machine. A bound-abrasive polisher is less likely to deform under load and changes in temperature. Significantly less abrasive is required in the finishing process, thereby reducing the cost of consumables. Removal rates can be high. Issues of concern are the physical integrity of the polishing tool in use at ~1000 rpm (e.g., resistance to dissolution from the aqueous coolant, or fracture/crumbling under load), the ability to efficiently smooth the glass surface without ruining the surface figure, and the polisher's performance for different glass types.

Information in the Russian literature, primarily from V. V. Rogov and colleagues, addresses the use of bound polishing abrasives in the form of pellets affixed to a cast iron plate. They investigated pellet composition, tool rotation rate, and load for a variety of glasses.[15–17] The resulting pellet media, called Aquapol®,[18] are described as dimensionally stable from 10°–80°C. By introducing a superfine diamond grinding stage to their process, a Moscow manufacturing enterprise was able to use Aquapol pellet polishing in distilled water to finish parts with some success. They noted, however, that the Aquapol materials "are rather brittle and possess low mechanical strength, which inevitably results in debris and crumbling at the edges of elements during operation and makes the tool unusable."[19] To avoid this problem, a form of nearly full contact Aquapol lap with a central hole was conceived and tested.[20] This concept proved successful for commercial-quality (e.g., figure accuracy tolerances to ~1 μm, rms surface roughness levels less than 10 nm) flat and spherical parts up to 50 mm in diameter. It was implemented at a number of factories throughout the former Soviet Union.

No information is available in the open literature regarding the use of bound-abrasive polishers in a ring tool geometry on CNC machine platforms. In this article we describe the development and testing of bound-abrasive compositions in three geometries: pellet, ring tool, and full-contact lap. We show that for several glass types, our compositions reduce rms surface roughness of initially fine ground surfaces to less than 2 nm in ~30 min. We demonstrate that bound-abrasive ring tools are compatible with CNC machine platforms, although maintaining or reducing surface figure errors is a problem that requires more study. We find, however, that it is feasible to use bound abrasives in *prepolishing* operations to remove grinding tool marks and dramatically shorten the time required for pitch polishing.

Key Performance Criteria, Variables, and Choices

There are five principle performance criteria for the successful development of a bound-abrasive polisher: First, the polisher must maintain its physical integrity during use at moderate to high velocities, in an aqueous environment, and under light to moderate load. Second, the polisher must release particles of polishing abrasive at a rate that promotes efficient removal of glass from the workpiece surface, but not so rapidly as to cause excessive tool wear, or so slowly that the tool surface "glazes" over with a solid film of binder. Third, the polisher must be manufactured in such a way that it exhibits reproducible performance under constant operating conditions. Fourth, the polisher must be capable of removing artifacts from grinding (e.g., tool marks, shallow scratches) to achieve an rms surface microroughness of less than ~2 nm in a reasonable period of time. Fifth, required surface figure tolerances must be met with the polisher.

Experiments on bound-abrasive polishers are complex because of the large number of variables and choices available in terms of polisher composition, manufacturing method, polisher geometry, workpiece glass type/shape, and polishing machine platform. The variables involved and the choices made for this work are summarized below.

1. Composition

Based upon the Russian work,[15] a successful bound-abrasive polisher consists of (in wt%) ~60 to 90/polishing agent, 5 to 25/binder, and 5 to 15/erosion promoter. Relative concentrations of abrasive/binder/erosion promoter are investigated here. Because of its high polishing efficiency for many soft and moderately hard glasses,[8] CeO_2 is the polishing abrasive of choice. An impure CeO_2/rare earth oxide blend, known as Polirit,[21,22] is used in the Aquapol media. It has a particle size of approximately 2 μm and is nominally 50% CeO_2. Polirit is available from several sources, and the variations in its composition from batch to batch have been noted.[23] We use three CeO_2 products with similar particle-size distributions and a range of purity levels from 50%–90%[24] (see Table 73.VII). The binder can be a polyimide, a phenolic (used in the Aquapol media), or an epoxy. From our earlier work[25] we have identified and use a low-viscosity, two-part epoxy[26] that can be readily impregnated with a high percentage of solids. The final ingredient in the polisher is an additive to promote erosion. Two types are studied here, separately and in combination, and their behavior is illustrated in Fig. 73.55. Ammonium chloride (NH_4Cl)[15] dissolves in the aqueous coolant during polishing to expose fresh abrasive particles to the work zone. Hollow alumina spheres[27] crush under mechanical loading and act as a form of controlled porosity to break up the binder material.

2. Manufacturing Method/Geometry

Because commercial mixing machines are costly and require large batch sizes, hand mixing was used to prepare all compositions according to a fixed methodology and cure schedule. Hand mixing has been found reliable and repeatable. The documentation given in this article is sufficient to transfer the manufacturing method to others. Mold geometry is limited to three forms in this work: pellet arrays (individual pellets waxed into arrays, or monolithic molded pellet arrays), rings, and full-contact laps.

3. Workpiece Glass Type/Shape

We concentrate on polishing commonly used optical glasses BK7,[28] SF7,[29] SK7,[29] SK14,[29] LaFN21,[29] TaFD5,[30] and fused silica,[31] whose Knoop hardness values fall in the range of ~3.4 to 6.7 GPa (350 to 680 kgf/mm^2) @ 200 gf.[32] Part shape is fixed at 35- to 50-mm diameter by 10 mm thick. Worked surfaces are either flat or spherical (convex 70-mm

Table 73.VII: Compositions and physical properties of Aquapol and selected experimental polishers.

ID#:	Composition, wt%*	Shore D Hardness air	Shore D Hardness water**	Young's Modulus GPa	Shear Modulus GPa	Density (g/cm^3)	Form Used***
Polirit CeO_2 50% pure[22]/ 2.0-μm size[42]							
#AS:	Aquapol standard unknown composition	90	66	18.0	7.8	3.99	spa rt
CeRite 415K CeO_2 75% pure[43] / 2.0-μm size[44]							
#1:	94 CeO_2 6 epoxy 0 e.p.	88	11	12.1	4.8	3.99	rt
#2:	93 CeO_2 7 epoxy 0 e.p.	78	23	11.3	4.5	3.96	mpa rt
#3:	75% CeO_2 10% epoxy 15% e.p. (all h.al.s.)	88	81	14.1	5.7	3.20	rt
CeRite 4251 CeO_2 50% pure[43]/1.5-μm size[44]							
#4:	75% CeO_2 10% epoxy 15% e.p. (all h.al.s.)	73	63	na	na	2.53	mpa rt
CeRox 1663 CeO_2 90% pure[43]/1.0-μm size[44]							
#5:	63% CeO_2 25% epoxy 12% e.p. (10 h.al.s. + 2 a.cl.)	75	na	12.4	4.7	2.64	mpa rt
#6:	85% CeO_2 10% epoxy 5% e.p. (all a.cl.)	70	60	na	na	3.40	mpa rt

* e.p.–erosion promoter (h.al.s.–hollow alumina spheres; a.cl.–NH_4Cl)
** 60-min soak @ 25°C in buffered pH 10 DI water with gentle agitation
*** spa–single-pellet array; mpa–molded-pellet array; rt–ring tool

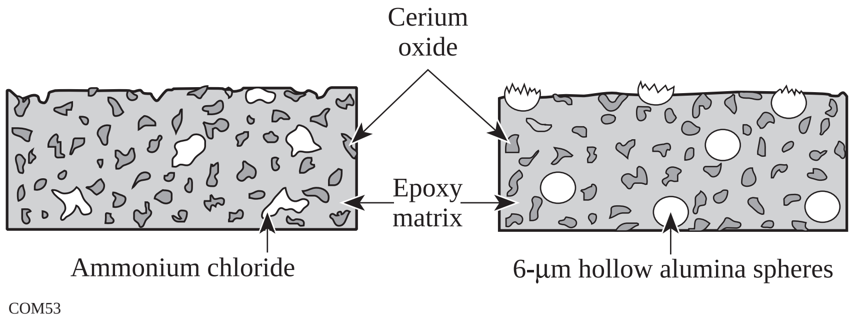

Figure 73.55
Ammonium chloride and hollow alumina spheres help promote erosion of the binder to expose fresh cerium oxide grains.

radius of curvature). Initial surface finish varies, depending on the method of preparation (loose abrasive grinding or ring tool generating).

4. Polishing Platforms

We evaluate polishing efficiency on three testbeds. A single-spindle polishing machine[33] is used for pellet polisher work with flat parts. This geometry is the easiest to implement and can be done with student assistants. Ring tool polishing trials are conducted on an Opticam SX CNC generating machine.[34] A collaborating company's[35] results from trials with full-contact polishers on semi-automated equipment are also reported.

Polisher Preparation and Bound-Abrasive Properties

To prepare a polisher, the abrasive and erosion promoter are dry mixed by hand and divided in half by weight. One portion is dispersed into two parts by weight of epoxy resin A, and the other is dispersed into one part by weight of epoxy hardener B. Once loaded with solids, A and B are separately hand mixed for 5 min, combined into a single batch, and hand mixed for an additional 10 min. A typical batch varies in weight from 50 g to 250 g. To prepare individual pellets similar in shape to the Aquapol media, the batch is poured into several 15-ml-capacity, plastic centrifuge tubes.[36] These tubes are tapped and mechanically vibrated to remove any entrapped air and cured at room temperature for 24 h. After curing, tubes are sliced open, and the cylindrical plugs are cut on a diamond saw[37] into 17.5-mm-thick pellets (12-mm diameter) with parallel surfaces. The individual pellets are mounted onto an aluminum plate with pitch or wax. Figure 73.56 illustrates the individual pellet polisher configuration. An alternative method uses an RTV silicone mold[38] containing an array of holes. The mold is treated with a mold-release agent,[39] and the batch is spread into it and cured. The 12-mm-diam pellets emerge in the form of a monolithic array (see Fig. 73.57), which is waxed to an aluminum plate. Other mold geometries are used to make solid rings. Full-contact laps are made by first creating a silicone mold master with a sample product part acting as a reference template.

For compositions containing >90-wt% solids, a small amount (10 ml per 100 g) of methanol[40] is added to resin A and hardener B to further reduce initial viscosities prior to loading in and mixing the solids. The use of methanol causes some cracking and fracture in molded rings during curing. This presents no problem since broken segments are glued together when being mounted onto a supporting ring tool chuck.

Mechanical properties testing for hardness and density verify the ability of different people to produce polishers with the same properties (±5%) when using our manufacturing method.[41] Table 73.VII gives property information for some experimental compositions. All six formulations function as bound-abrasive polishers, as will be demonstrated in the following sections. It is instructive to compare their physical properties with those of the standard hardness Aquapol media.

The Aquapol composition #AS is the hardest (Shore D) and least compliant (Young's modulus) material in Table 73.VII. It is brittle and easily fractured during routine handling and loading against a glass surface. By using an epoxy instead of a phenolic binder, we reduce hardness and increase compliance to improve handling. All experimental compositions show this feature. The CeO_2 concentration is so high in #1 and #2 that an erosion promoter is not necessary. A potential disadvantage to such a high abrasive concentration is the reduction of material resistance to disintegration in water. Measurements of hardness after soak tests in pH 10 water (a typical coolant requirement for CNC glass grinding machines[45]) show that compositions #1 and #2 are less robust.

A 1% increase in epoxy concentration (#1 to #2) improves soak test durability for a modest sacrifice in hardness. A further 3% increase to 10 wt% (#3, #4, #6) and higher (#5) greatly enhances soak test durability to that seen for Aquapol. (Soak

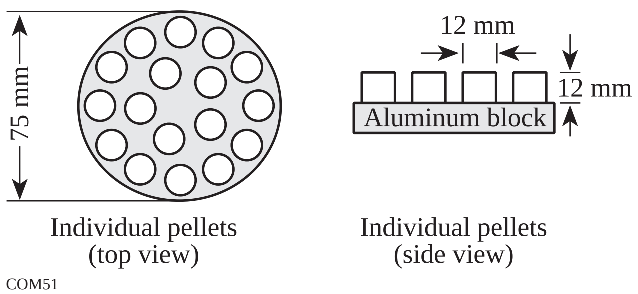

Figure 73.56
Setup for pellet array polisher manufactured from single pellets.

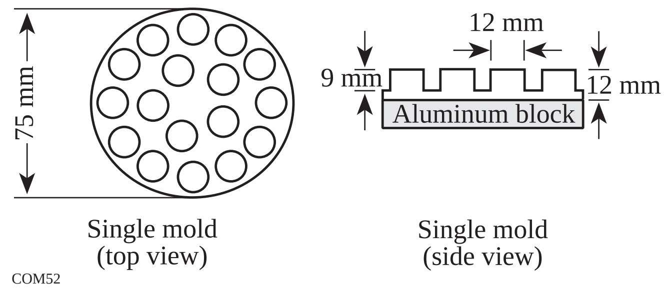

Figure 73.57
Setup for molded pellet array polisher.

tests, however, are not necessarily the best measure of a bound-abrasive polisher's durability in use as discussed later.) In addition to acting as erosion promoters, hollow alumina spheres in #3, #4, and #5 help to maintain high hardness and stiffness at high epoxy concentrations. Table 73.VII shows that, from a fabrication perspective, viable polishers may be manufactured from any of the three commercial CeO_2 abrasives.

Experimental Results for Pellet Laps

The objective was to evaluate the ability of flat, pellet array laps to reduce rms surface roughness of loose-abrasive–ground, flat glass parts to <2 nm in a fixed 30-min polishing cycle. Work reported is for compositions #5 and #6. Freshly made pellet array laps were dressed to expose the abrasive by working against a cast iron plate with ~9 μm alumina.[46] This also trued the surface. Glass parts of differing composition and physical properties were conditioned in the same manner to establish an initial ground surface whose rms surface roughness values were between 300 and 500 nm.[47] Work was carried out on a single-spindle machine,[33] lap on bottom, with the following setups: spindle speed, 35 rpm; eccentric speed, 58 rpm; front center adjustment, 0 mm; back center adjustment, 25 mm; load, 17.2 kPa (2.5 psi). The coolant was DI water, directed onto the lap and recirculated without filtration at a rate of ~200 ml/min. Results, summarized in Table 73.VIII, show that composition #5 works well for polishing out glasses with moderate hardness values. Composition #6 (higher CeO_2 concentration, less erosion promoter) works well for harder glasses, but twice as much time is required to polish down to below 2 nm rms. Other work (not reported here) shows that these polishers do not perform as well for crystalline materials (Si, Ge, CaF_2, ZnSe) whose hardness values fall outside the test range.

Table 73.VIII: Polishing results for bound-abrasive pellet array laps after 30 min.

Composition	Glass	(Hardness*)	Final rms[47] (nm)
#5	SF7	(3.4)	1
	SK7	(4.8)	1
	BK7	(5.1)	1
#6	fused silica	(6.5)	1.5 (60 min)
	TaFD5	(6.7)	1.5 (60 min)

*Knoop hardness, GPa @ 200 gf[32]

Molded Ring Tool Polishers

Several molded ring tool polishers were evaluated on the Opticam SX CNC generating machine.[34] Figure 73.58 shows the schematic of a ring tool polisher against a glass part. Major differences exist between the single-spindle machine used for flat pellet array polishing studies and the Opticam SX. The single-spindle machine utilizes a constant force approach for the lapping process. The Opticam SX uses a constant infeed rate for the cutting process with metal-bonded, diamond ring tools. The single-spindle machine operates at relatively low speeds and pressures, and experiments can be conducted with any desired coolant. Minimum tool and part speeds on the Opticam SX are 1000 rpm and 150 rpm, respectively. The coolant used for the SX polishing experiments is a filtered, high-viscosity grinding coolant, complete with corrosion inhibitors, defoamers, and fungicides.[48]

All compositions except #5 were manufactured in the form of solid and segmented ring tools for testing on the Opticam SX. Both flat and convex surfaces on either BK7 or SK14 glass (similar in hardness to SK7) were polished. All parts were prepared for polishing with the ring tool grinding strategy summarized at the beginning of this article. Initial values of rms surface roughness were from 25 to 35 nm,[47] and the presence of residual grinding tool marks was noted (see below) on all parts. The programmed depth of cut (DOC) for each trial varied, but most trials had a 60-μm DOC and required ~15 min to complete. (It was not possible to measure the actual amount of glass material removed in a trial, due to the slightly compliant nature of the tools.) A wear path ~1 mm wide was typically observed on a tool surface after a trial. Tool wear was observed to be higher for compositions with higher CeO_2 concentrations. Table 73.IX shows that these polishers can reduce rms surface roughness to ≤1 nm. All in-house polishers maintained their mechanical integrity at speeds of 1000 rpm. There were no adverse effects noted on the guideways of the machine. In contradiction to the soak test results, compositions #1 and #2 held up well in the coolant spray, possibly because the time of exposure is reduced by 4× compared to that of the soak test. The Aquapol AS composition tool exhibited serious erosion problems in the commercial coolant, so it was therefore used for shorter, 5-min runs with a DOC of 30 μm. For these short runs, the standard Aquapol material performed well.

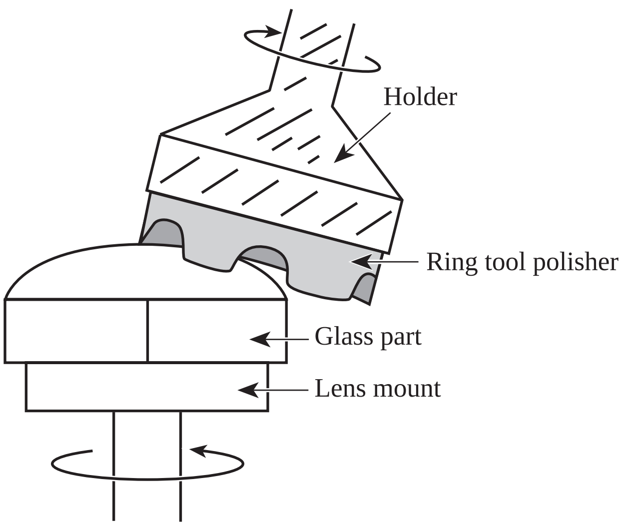

Figure 73.58
Schematic of bound-abrasive ring tool polisher.

It is useful if, as part of the polishing process, the polisher can remove diamond ring tool grinding marks. Referred to as "cutter" marks, they are produced on the part surface as a result of relative vibrations between the machine and the part and exhibit a circumferential periodicity that varies from 2 mm near part center to 10 mm near part edge. Figure 73.59 shows a radial profile scan[49] of a BK7 surface ground with a 10- to 20-μm diamond ring tool. The cutter marks have an amplitude of ~1000 Å and an edge periodicity of ~10 mm. Pitch laps and the high-cerium-oxide-concentration compositions #1 and #2 are very effective at removing cutter marks, as shown in Fig. 73.60. Other polisher compositions are similarly effective.

Attempts to reduce surface figure errors with bound-abrasive ring tools were not successful. Initial p–v surface figure values of 0.3 μm (λ/2) were seriously degraded by the tendency of the ring to polish a 0.5- to 2.0-μm-deep hole into the part center, regardless of shape (flat or convex sphere). A bound-abrasive ring tool polisher causes degradation to the surface figure when it does not wear rapidly enough to expose fresh CeO_2. The result is constant-force polishing similar to conventional polishing, on a machine designed to remove material at a constant infeed using diamond ring tools. The constant-force polishing causes excessive dwell in the part center. This can be avoided by going to a different bound-abrasive polishing tool shape and contact configuration.

Table 73.IX: Results for bound-abrasive ring tool polishing on the Opticam SX.

Composition	Part Shape	Glass	Programmed DOC (μm)	Final rms[47] (nm)	Tool Wear	Tool Marks Removed
#AS	flat	BK7	30	0.8	higher	yes
#1	flat	BK7	60	1.8	higher	no
#2	flat	BK7	120	1.10	higher	yes
	convex	SK14	60	0.6		yes
#3	flat	BK7	90	1.0	lower	yes
#4	flat	BK7	60	1.1	lower	yes
#6	convex	SK14	60	0.9	lower	no

An alternative polishing configuration, called contour mode polishing, is illustrated in Fig. 73.61. In this geometry, the peripheral face of the tool is used to remove material by following a tool path that traverses over the surface of the rotating workpiece (see infeed path motion in Fig. 73.61). A new aspheric generating machine, the Opticam AG, was recently delivered to the COM.[50] It possesses the correct configuration for use as a testbed for future trials of bound-abrasive polishers in a new form, that of a contour tool. Our expectation is that it should be possible to significantly reduce figure degradation when polishing in this manner.

Molded Full-Contact Polishers

Several full-contact polishers were molded from composition #6 for a local optics company[35] to test on LaFN21 glass (Knoop hardness, 6.18 GPa @ 200 gf). The polishers were made to a specified 11.48-mm radius of curvature and 22-mm diameter by using a sample lens as the mold master. After release from the mold, the polishers were modified by carving grooves in their centers to reduce center contact and help maintain the optical figure of the part during the polishing cycle. Due to constraints on the semiautomated machines at the company, the polishers were used with a cerium oxide polishing slurry instead of deionized water. Results indicate that the company can reduce overall finishing time by 50% by using full-contact molded polishers in a prepolishing stage. Due to the stiffer nature of these polishers compared to pitch, they can be used at higher pressures and spindle speeds to increase material-removal rates without degrading surface figure.

A microlens manufacturer[51] used molded bound-abrasive polishers made from the compositions and manufacturing methods described in this paper to aid in the production of $\lambda/4$ surfaces. Opticians preferred these polishers because their stiffness helped in maintaining figure.

Conclusions

We describe the development of bound-abrasive polishers using any of three commercial CeO_2 abrasives in six compositions. An epoxy is used as the binder. Useful polishing is achieved without an erosion promoter by using very high concentrations of abrasive. An erosion promoter is required to help break up the epoxy binder and expose abrasive grains at lower abrasive concentrations. Performance results are given for three polisher configurations: pellet array, ring tool, and full contact. All compositions work well, but the ones with higher CeO_2 concentration appear best for harder glasses.

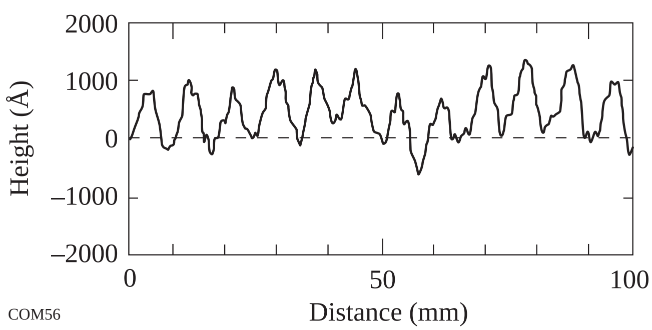

Figure 73.59
Radial profile scan showing tool marks remaining on a part surface from ring-tool-generating process.

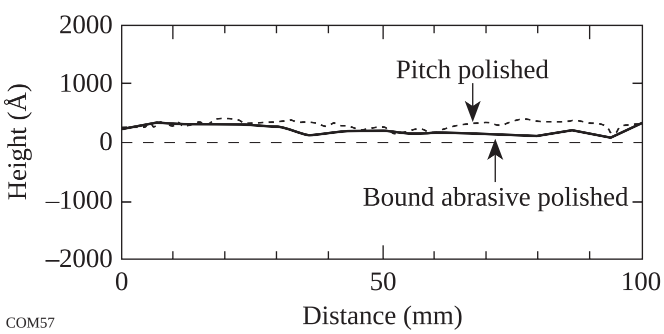

Figure 73.60
Removal of tool marks by either pitch polishing or bound-abrasive ring tool polishing.

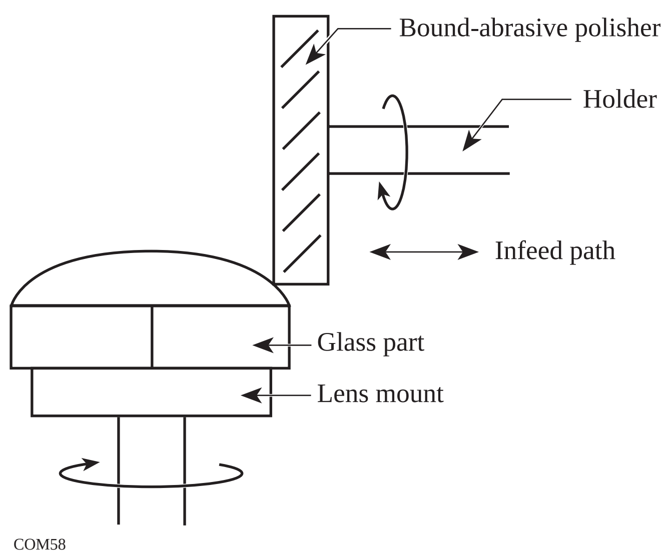

Figure 73.61
Concept for bound-abrasive contour polishing.

These polishers meet most of the performance criteria established for them. They maintain their physical integrity in aqueous coolants, under moderate loads, and at moderate to high velocities. They polish efficiently and are capable of reducing rms surface roughness of optical glasses from ~400 nm to ~1 nm in 30 min. The polishers are readily manufactured using simple process steps and have reproducible properties. They are compatible with Opticam-type CNC generating machines and can act as a fourth tool in an automatic tool changer to remove tool marks left from the last diamond ring tool grinding operation.

The issue of surface figure correction during polishing has not been successfully resolved with the bound-abrasive *ring* tool configuration, but a bound-abrasive *contour* tool mode of polishing is proposed as a solution. Finally, industry trials have demonstrated that the technology is transferable and helps to reduce overall production times when incorporated into the manufacturing process.

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REFERENCES

1. J. C. Lambropoulos, T. Fang, P. D. Funkenbusch, S. D. Jacobs, M. J. Cumbo, and D. Golini, Appl. Opt. **35**, 4448 (1996).
2. J. C. Lambropoulos, S. D. Jacobs, B. E. Gillman, F. Yang, and J. Ruckman, "Subsurface Damage in Microgrinding Optical Glasses," to be published in the *Proceedings of the Fifth International Conference on Advances in the Fusion and Processing of Glass*, Toronto, Canada, 27–31 July 1997.
3. D. Golini and W. Czajkowski, Laser Focus World, July 1992, 146.
4. Our vendors include Scomac, Inc., Bergen, NY 14416 and H & C Tool Supply, Rochester, NY 14611, a distributor for Norton Superabrasives.
5. T. S. Izumitani, *Optical Glass*, American Institute of Physics Translation Series (American Institute of Physics, New York, 1986), Chap. 4, pp. 91–146.
6. M. J. Cumbo, D. Fairhurst, S. D. Jacobs, and B. E. Puchebner, Appl. Opt. **34**, 3743 (1995).
7. H. H. Karow, *Fabrication Methods for Precision Optics* (Wiley, New York, 1993), Chap. 5, p. 463.
8. L. M. Cook, J. Non-Cryst. Solids **120**, 152 (1990).
9. G. W. Fynn and W. J. A. Powell, in *Cutting and Polishing Optical and Electronic Materials*, The Adam Hilger Series on Optics and Optoelectronics, 2nd ed. (A. Hilger, Bristol, England, 1988), Chap. 3, p. 83.
10. N. J. Brown, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-80301 (1977).
11. M. Ando *et al*., Nanotechnology **6**, 111 (1995).
12. A. P. Bogdanov *et al*., J. Opt. Technol. **61**, 474 (1994).
13. T. W. Drueding *et al*., Opt. Eng. **34**, 3565 (1995).
14. D. Golini, S. Jacobs, W. Kordonski, and P. Dumas, in *Advanced Materials for Optics and Precision Structures*, edited by M. A. Ealey, R. A. Paquin, and T. B. Parsonage, Critical Reviews of Optical Science and Technology (SPIE, Bellingham, WA, 1997), Vol. CR67, pp. 251–274.
15. A. P. Denisenko *et al.*, Russian Patent No. SU 1263513 A1 (October 1986), USSR certificate No. 88333, trademark rights.
16. V. V. Rogov *et al*., Sov. J. Opt. Technol. **56**, 33 (1989).
17. V. V. Rogov, Sov. J. Opt. Technol. **58**, 366 (1991).
18. Aquapol® product literature, Institute for Superhard Materials, Academy of Sciences of the Ukranian SSR, Kiev, Ukraine (1992).
19. V. M. Al'tshuller, S. A. Gerasimov, and V. P. Pushechnikov, J. Opt. Technol. **61**, 470 (1994).
20. S. I. Zakharov and O. V. Tapinskaya, Sov. J. Opt. Technol. **58**, 519 (1991).
21. N. L. Kudryavtseva *et al*., Sov. J. Opt. Technol. **44**, 347 (1977).
22. N. L. Kudryavtseva, N. E. Khar'kov, and G. S. Khodakov, Sov. J. Opt. Technol. **50**, 378 (1983).
23. M. Yu. Konyukhov *et al*., Sov. J. Opt. Technol. **58**, 798 (1991).
24. Transelco CeRite 415K, CeRite 4251, and Rhone Poulenc Cerox 1663, distributed by Universal Photonics, Inc., Hicksville, NY 11801.
25. W. Ng, B. E. Puchebner, S. D. Jacobs, J. L. Currin, B. McAvoy, D. Yungk, S. M. Gracewski, and P. D. Funkenbusch, in *Optical Fabrication and Testing Workshop*, Vol. 13, 1994 OSA Technical Digest Series (Optical Society of America, Washington, DC, 1994), pp. 114–116.
26. Epo-Tek B9131-2®, two-component "power laser adhesive," Epoxy Technology, Inc., Billerica, MA 01821.
27. Plasma alumina, low-density, microporous, hollow aluminum oxide spheres, 6-μm diameter, P.Q. Corporation, Conshohocken, PA 19428.
28. Ohara Corporation, Somerville, NJ 08876-3519.

29. Schott Glass Technologies, Inc., Duryea, PA 18642.

30. Hoya Optics, Inc., Fremont, CA 94538.

31. Fused silica, Code 7940, Corning Inc., Corning, NY 14831.

32. Schott Optical Glass Catalog (1989); Hoya Optical Glass Catalog (1989); Corning fused-silica product literature (1997).

33. R. Howard Strasbaugh (Model 6DE-DC-1), Woodbury, CT 06798.

34. Opticam® SX (renamed OptiPro 150), OptiPro Systems Inc., Ontario, NY 14519.

35. Optimax Systems, Inc., Ontario, NY 14519.

36. Catalog #21008-089, VWR Scientific Products, West Chester, PA 19380.

37. Buehler Isomet low-speed saw, Buehler Ltd., Lake Bluff, Il 60044.

38. Dow Corning RTV 3110, distributed by Wolcott-Park, Rochester, NY 14617.

39. ReleasaGen®, paintable ester mold release spray, IMS Inc., Chagrin Falls, OH 44022.

40. MX0485-7 methanol GR (anhydrous), EM Science, Gibbstown, NJ 08027.

41. B. E. Puchebner and S. D. Jacobs, in *Optical Manufacturing and Testing*, edited by V. J. Doherty and H. P. Stahl (SPIE, Bellingham, WA, 1995), Vol. 2536, pp. 256–264.

42. N. L. Kudryavtseva *et al*., Sov. J. Opt. Technol. **46**, 478 (1979).

43. Universal Photonics Product Catalog (1996), p. 14.

44. Measurements performed on a Horiba LA 900 Laser Scattering Particle Analyzer®, Horiba Instruments, Inc., Irvine, CA 92714.

45. B. E. Gillman, B. M. Reed, M. A. Atwood, J. L. Ruckman, D. J. Quesnel, T. T. Ochinero, and S. D. Jacobs, in *Optical Manufacturing and Testing II*, edited by H. P. Stahl (SPIE, Bellingham, WA, 1997), Vol. 3134, pp. 198–204.

46. Microgrit Abrasives Corporation, Westfield, MA 01086.

47. NewView 100®, white-light interferometer, 0.25 mm × 0.35 mm, areal, 20X Mirau, Zygo Corporation, Middlefield, CT 06455. Each roughness measurement reported is an average of measurements made at three sites over the part surface, avoiding center and edges.

48. LOH K-40 Coolant, LOH Optical Machinery, Inc., Germantown, WI 53022.

49. Mark IV xp phase shifting interferometer, Zygo Corporation, Middlefield, CT 06455. Using a high-pass, fast Fourier transform filter, the software options allow a line scan to be taken around the part at a fixed radius from the part center (14 mm), defined as a radial scan.

50. Moore Tool Company, Bridgeport, CT 06607.

51. Model, Inc./Integrated Endoscopy, Irvine, CA 92618.