Bound-abrasive polishers for optical glass

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Polishing abrasives that have been bound in a solid matrix can offer several potential advantages over loose-abrasive processes with pitch or polyurethane laps for finishing of optics. These advantages include polishing efficiency, temperature stability, cost of consumables, and compatibility with computer numerically controlled generating machines. Unfortunately, little has been published on bound-abrasive polishers, and very few commercially available products exist. We have developed several compositions and manufacturing techniques that show promise for polishing a variety of optical glasses. We establish the various criteria for a successful bound-abrasive polisher. The numerous variables to be considered in designing these polishers are identified, and the results of screening experiments are used to find successful compositions. Polishing experiments with bound abrasives in arrays of pellets, as ring tools, and as full-contact laps are described.

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1. Introduction

Optical finishing of glass consists of generating (grinding) and polishing stages. In grinding, brittle fracture is performed on a workpiece by use of a series of two or three bound-abrasive grinding tools. These tools are composed of diamonds in a metal or a resin matrix. The generating process starts with a coarse ($\sim$60 μm) diamond tool and concludes with a medium ($\sim$15 μm) and a fine ($\sim$3 μm) tool (optional). Reliable, repeatable, deterministic microgrinding with ring tools [using Opticam computer numerically controlled (CNC) machining platforms developed at the Center for Optics Manufacturing] produces spherical surfaces with rms surface microroughness of $\sim$10 nm,[1] subsurface damage with a depth of less than 3 μm[2] and peak-to-valley (p–v) surface shape errors less than 0.3 μm ($\lambda/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 with 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 high-precision, subnanometer surface finishes on glass. Although much progress has been made in understanding slurry-fluid chemistry,[8] slurry-workpiece electrostatics,[6] and the interaction among the polishing abrasive, the polisher, and the part,[5] the conventional pitch-polishing process continues to be heavily iterative. 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 the finishing time in rapid prototyping. Subaperture processing technologies with small pitch-surfaced tools[11] or ion beams[12,13] have been found to be useful in selected applications. A newly developed process, magnetorheological finishing, has demonstrated the ability to

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polish out flats, concave or convex spheres, or aspheres on a magnetic fluid lap with no specialized tooling rapidly and automatically.[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 onboard 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 makes it possible to perform finishing 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 the cost of consumables is reduced. 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 and crumbling under load), the ability to smooth the glass surface efficiently without ruining the surface figure, and the polisher's performance for different glass types.

In the Russian literature that addresses the use of bound polishing abrasives that are in the form of pellets affixed to a cast iron plate, the pellet composition, tool rotation rate, and load for a variety of glasses were investigated.[15–17] The resulting pellet media, called Aquapol,[18] are described as dimensionally stable from 10° to 80 °C. By introducing a superfine diamond grinding stage to their process, a Moscow manufacturing enterprise, Optika State Scientific Manufacturing Organization, 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 and rms surface roughness levels less than 10 nm) flat and spherical parts as wide as 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 paper we describe the development and the 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. Although maintaining or reducing surface figure errors is a problem that requires more study, we demonstrate that bound-abrasive ring tools are compatible with CNC machine platforms. We find, however, that it is feasible to use bound abrasives in prepolishing operations so that grinding tool marks are removed and the time required for pitch polishing is shortened drastically.

2. 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 material. 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 a rms surface microroughness of less than ~2 nm in a reasonable period. Fifth, the 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 or shape, and polishing machine platform. The variables involved and the choices made for this study are summarized below.

—Composition: Based on a Russian study,[15] a successful bound-abrasive polisher consists of (in weight percent) ~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% to 90%[24] (see Table 1 below). The binder can be a polyimide, a phenolic (used in the Aquapol media), or an epoxy. From our earlier study[25] we have identified and used 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 com-

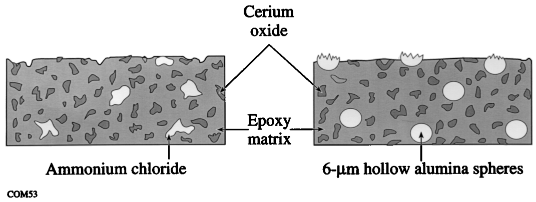

Fig. 1. Ammonium chloride and hollow alumina spheres help to promote erosion of the binder to expose fresh cerium oxide grains.

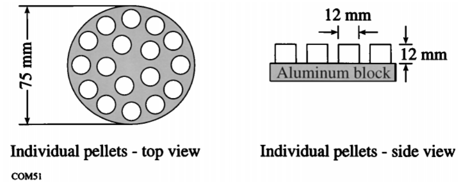

Fig. 2. Setup for pellet array polisher manufactured from single pellets.

bination, and their behavior is illustrated in Fig. 1. Ammonium chloride (NH_4Cl) (Ref. 15) dissolves in the aqueous coolant during polishing to expose fresh abrasive particles to the work zone. Hollow alumina spheres[27] become crushed under mechanical loading and act as a form of controlled porosity to break up the binder material.

—Manufacturing Method and 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 paper is sufficient to transfer the manufacturing method to others. Mold geometry is limited to three forms in this study: pellet arrays (individual pellets waxed into arrays or monolithic molded pellet arrays), rings, and full-contact laps.

—Workpiece Glass Type and 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 from ~3.4 to 6.7 GPa (350–680 kgf/mm^2) at 200 gf.[32] The part shape is fixed at a 35- to 50-mm by 10-mm-thick diameter. Worked surfaces are either flat or spherical (convex 70-mm radius of curvature). Initial surface finish varies, depending on the method of preparation (loose-abrasive grinding or ring tool generating).

—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] Optimax Systems, Inc.,[35] a company that collaborated with the authors, performed trials with full-contact polishers on semiautomated equipment. Their results are also reported.

3. Polisher Preparation and Bound-Abrasive Properties

To prepare a polisher, the abrasive and the 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 hand mixed separately for 5 min, combined into a single batch, and hand mixed for an additional 10 min. A typical batch varies in weight from 50 to 250g. 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 vibrated mechanically to remove any entrapped air, and they are cured at room temperature for 24 h. After curing, the tubes are sliced open, and the cylindrical plugs are cut by 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 2 illustrates the individual pellet polisher configuration. An alternative method uses a 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-diameter pellets emerge in the form of a monolithic array (Fig. 3), 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/100 g) of methanol[40] is added to resin A and hardener B to reduce initial viscosities further before 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 1 gives property information for some experimental compositions. All six formulations function as bound-abrasive polishers, as is demonstrated below. It is instructive to compare their physical properties with those of the standard hardness Aquapol media.

The Aquapol composition Aquapol standard (AS) is the hardest (Shore D) and least compliant (Young's

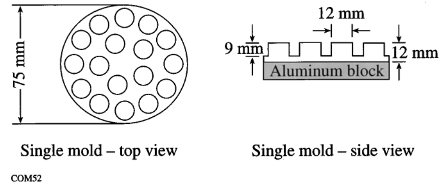

Fig. 3. Setup for molded pellet array polisher.

Table 1. Compositions and Physical Properties of Aquapol and Selected Experimental Polishers

ID No.: Composition, wt.%[a]	Shore D Hardness Air	Shore D Hardness Water[b]	Young's Modulus GPa	Shear Modulus GPa	Density (g/cm^3)	Form Used[c]
Polirit CeO_2 50% pure[d]/2.0-μm size[e]						
AS: Aquapol standard unknown composition	90	66	18.0	7.8	3.99	spa rt[c]
CeRite 415K CeO_2 75% pure[f]/2.0-μm size[g]						
1: 94 CeO_2, 6 epoxy, 0 e.p.[a]	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[c]
3: 75% CeO_2, 10% epoxy, 15% e.p. (all h.al.s.[a])	88	81	14.1	5.7	3.2	rt
CeRite 4251 CeO_2 50% pure[f]/1.5-μm size[g]						
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[f]/1.0-μm size[g]						
5: 63% CeO_2, 25% epoxy, 12% e.p. (10 h.al.s + 2 a.cl.[a])	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

[a]e.p., erosion promoter (h.al.s., hollow alumina spheres; a.cl., NH_4Cl)
[b]60-min soak at 25 °C in buffered pH 10 DI water w/gentle agitation
[c]spa, single-pellet array; mpa, molded-pellet array; rt, ring tool
[d]Ref. 22
[e]Ref. 42
[f]Ref. 43
[g]Ref. 44

modulus) material in the table. 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 compositions 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 (compositions 1 to 2) improves soak-test durability for a modest sacrifice in hardness. A further 3% increase to 10 wt. % (compositions 3, 4, and 6) and higher (composition 5) greatly enhances soak-test durability to that seen for Aquapol. (However, as discussed below, soak tests are not necessarily the best measure of bound-abrasive polisher durability.) In addition to acting as erosion promoters, the hollow alumina spheres in compositions 3–5 help to maintain high hardness and stiffness at high epoxy concentrations. The table shows that, from a fabrication perspective, viable polishers may be manufactured from any of the three commercial CeO_2 abrasives.

Table 2. Polishing Results for Bound-Abrasive Pellet Array Laps after 30 min

Composition	Glass	(Hardness[a])	Final rms,[b] (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)

[a]Knoop hardness, GPa at 200 gf (Ref. 32)
[b]Ref. 47

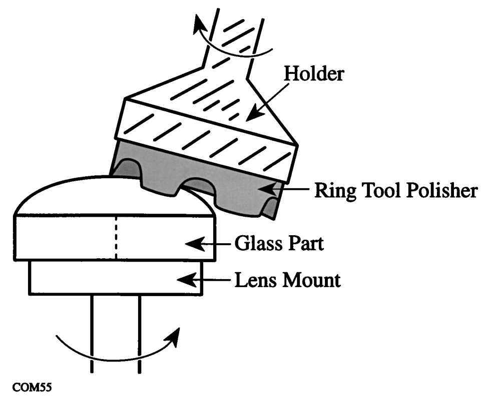

Fig. 4. Bound-abrasive ring tool polisher schematic.

4. 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. Research reported is for compositions 5 and 6. We dressed freshly made pellet array laps 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] Research was carried out on a single-spindle machine[33] with the lap on the bottom and 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 de-ionized (DI) water, directed onto the lap and recirculated without filtration at a rate of ~200 ml/min. Results, summarized in Table 2, show that composition 5 works well for polishing out glasses with moderate hardness values. Composition 6 (higher CeO_2 concentration and less erosion promoter) works well for harder glasses, but twice as much time is needed to polish down to below 2 nm rms. Other research (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.

5. Molded Ring Tool Polishers

Several molded ring tool polishers were evaluated on the Opticam SX CNC generating machine.[34] Figure 4 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 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 above. 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, owing 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 3 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 was reduced by 4× compared with that of the soak test. The Aquapol AS composition tool exhibited serious erosion problems in the commercial coolant, so it was used for shorter 5-min runs with a DOC of 30 μm. For these short runs, the AS material performed well.

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 5 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

Table 3. Results for Bound-Abrasive Ring Tool Polishing on the Opticam SX

Composition	Part Shape	Glass	Programmed DOC (μm)	Final rms[a] (nm)	Tool Wear	Tool Marks Removed
AS	flat	BK7	30	0.8	higher	yes
1	flat	BK7	60	1.8	higher	yes
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

[a]Ref. 47

2 are very effective at removing cutter marks, as shown in Fig. 6. 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 a 2.0-μm-deep hole into part center, regardless of the 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 with 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.

An alternative polishing configuration, called contour-mode polishing, is illustrated in Fig. 7. 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. 7). A new, aspheric generating machine, the Opticam AG, was recently delivered to the Center for Optics Manufacturing.[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.

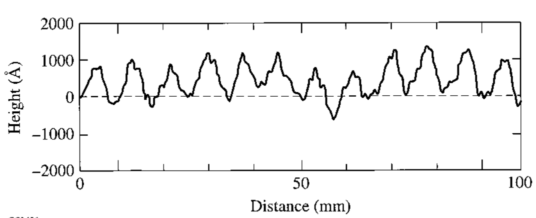

Fig. 5. Radial profile scan showing tool marks remaining on a part surface from the ring tool generating process.

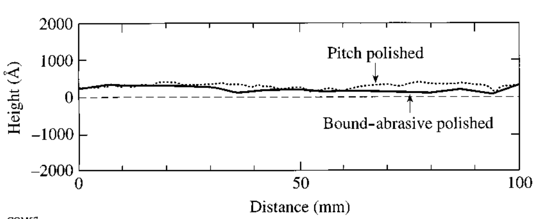

Fig. 6. Removal of tool marks by either pitch polishing or bound-abrasive ring tool polishing.

6. Molded Full-Contact Polishers

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

Model, Inc./Integrated Endoscopy[51] used molded

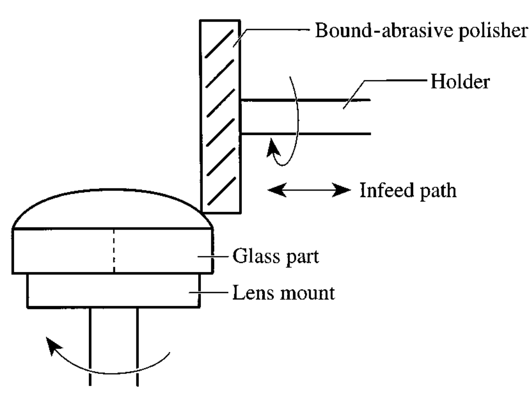

Fig. 7. Concept for bound-abrasive contour polishing.

bound-abrasive polishers made from the compositions and the manufacturing methods described in this paper to aid in the production of $\lambda/4$ surfaces. Opticians preferred these polishers because their stiffness helped to maintain the figure.

7. Conclusions

We describe the development of bound-abrasive polishers with any of three commercial CeO_2 abrasives in six compositions. An epoxy is used as the binder. We achieved useful polishing without an erosion promoter by using very high concentrations of abrasive. An erosion promoter is needed 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.

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 $\sim$400 to $\sim$1 nm within 30 min. The polishers are readily manufactured with 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 resolved successfully 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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