Magnetorheological Finishing—A Deterministic Process for Optics Manufacturing

Finish polishing of optics with magnetic media has evolved extensively over the past decade. Of the approaches conceived during this time, the most recently developed process is called magnetorheological finishing (MRF). In MRF, a magnetic field stiffens a fluid suspension in contact with a workpiece. The workpiece is mounted on the rotating spindle of a computer-numerically-controlled (CNC) machine. Driven by an algorithm for machine control that contains information about the MRF process, the machine deterministically polishes out the workpiece by removing microns of subsurface damage, smoothing the surface to a microroughness of 10 Å rms, and correcting surface figure errors to less than 0.1 μm peak-to-valley (p-v). Spheres and aspheres can be processed with the same machine setup using the appropriate machine program. This article describes MRF and gives examples that illustrate the capabilities of a pre-prototype machine located at the Center for Optics Manufacturing (COM).

Background

Finish polishing of optics is defined here to be the production of a surface to within 0.25 μm p-v of the specified figure, accompanied by sufficient material removal to eliminate subsurface damage and to achieve a microroughness of 10 Å rms. Classical finishing processes employ precisely shaped, viscoelastic pitch or polyurethane foam-faced laps to transfer pressure and velocity through an abrasive slurry to the workpiece. Material is removed by chemical and mechanical interactions among the abrasive (typically micron- to submicron-size cerium oxide or aluminum oxide), the carrier fluid (water), and the workpiece.

Strong technical and economic incentives exist for developing alternative finishing processes that use laps whose shapes are not permanently fixed, but can be controlled and changed with the application of an external field. The cost for design, manufacture, and storage of numerous fixed laps, each with a different surface curvature, would be eliminated. It would also be easy to create unique lap shapes for finishing aspheric and other nonstandard surfaces. Innovative work has been done by several research groups throughout the world to introduce magnetic media to the optics finishing process.

Magnetic media-assisted finishing has been studied in Japan for many years. In 1984, Y. Tani and K. Kawata[1] reported experiments with the geometry shown in Fig. 63.39. The principal of operation was the creation of magnetobuoyant forces that acted on nonmagnetic abrasives (silicon carbide, 4-μm diam, 40 vol.%) in a magnetic fluid (a ferrocolloid-magnetite, Fe_3O_4, 100- to 150-Å diam in eicosyl naphthalene), placed in a nonuniform magnetic field (1-kG approximate field strength). The magnetic field gradients created by a flat lap array of permanent magnets caused the abrasive grains to levitate upward into contact with the work. Motor-driven rotation of the main spindle caused the work (a set of three acrylic plates, 20 mm in diameter) to move over the abrasives that were localized in the regions of minimum magnetic field.

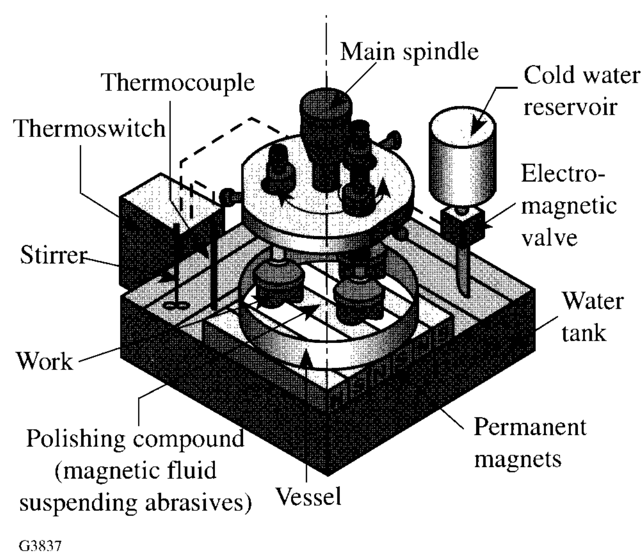


Fig. 63.39
Polishing of acrylic plates with SiC abrasives in a magnetic fluid composed of 150-Å-diam magnetite particles. The pole pieces serve as the reference lapping surface for the workpiece. (From Ref. 1.)

Material was removed at the rate of 2 μm/min across the entire part, and a 10× reduction in surface roughness to 400-Å Rmax was observed after 1 h. (Rmax denotes peak-to-valley roughness.) The authors noted significant thermal control problems in the slurry.

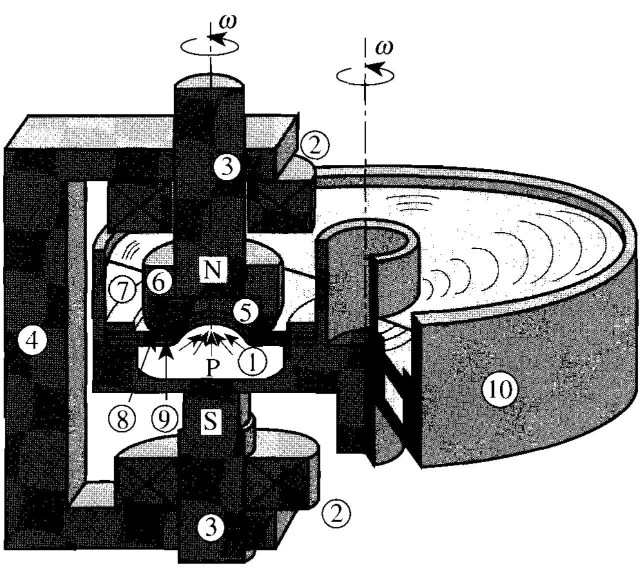
Related work was reported by Y. Saito *et al.* in 1987, again for acrylic plates in an aqueous-based ferrocolloid slurry.[2] Confinement of polishing abrasives to the work zone was a problem. The pressures generated by these two approaches were inadequate to polish glass, and there was no possibility for surface figure control.

Based upon work of Kurobe,[3] Suzuki *et al.*[4] made significant advances with the machine geometry shown in Fig. 63.40. By sealing the ferrocolloidal media in a brass trough with a flexible, polyurethane-rubber cover, they could direct considerably more pressure (10–25 kPa for 8–10 kG) to a colloidal silica slurry in contact with the work. It was possible to finish hard materials against a magnetically shaped polyurethane lap. Nonplanar surfaces could be polished by suitably contouring the magnet pole cap. In 1989, they reported smoothing a lithium niobate surface of 50-mm radius of curvature from 1500-Å to 100-Å Rmax (17 Å rms) in 30 min. The spherical surface figure error was reduced from 0.4 to 0.3 μm p-v.

More recently, in 1993, these researchers demonstrated the ability to polish aspheric surfaces on 40-mm-diam Pyrex® glass parts with removal rates of 2 to 4 μm/h.[5] One drawback to this approach was a lack of edge control. Another serious impediment to commercialization was the need for an inventory of customized pole caps, uniquely shaped to each desired surface form.

Introduction to Magnetorheological Finishing (MRF)

The most recent approach to processing optics with magnetic fluids is magnetorheological finishing (MRF). This technology was initiated in Minsk, Belarus by Kordonski, Prokhorov, and coworkers,[6,7] as an outgrowth of work with intelligent fluids for clutches, shock absorbers, and vibration isolators. The concept of MRF is shown in Fig. 63.41. A suspension of noncolloidal magnetic particles and polishing abrasives is contained in a vessel, or trough. Rotation of the trough delivers the suspension to the surface of a spindle-mounted workpiece. With the application of a dc magnetic field in the vicinity of the workpiece, the suspension stiffens to form a small pressure spot that contacts and conforms to the workpiece. The magnetic-field-stiffened suspension constitutes a lap, and the constant flow of magnetic particles and



1. Magnetic fluid
2. Coil
3. Iron pole
4. Yoke
5. Workpiece
6. Jig or chuck
7. Polishing abrasive
8. Polyurethane pad
9. Rubber sheet
10. Brass vessel

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Fig. 63.40
Apparatus for polishing with a pad whose shape is defined by a magnetic field acting on a confined magnetic fluid. (From Ref. 2.)

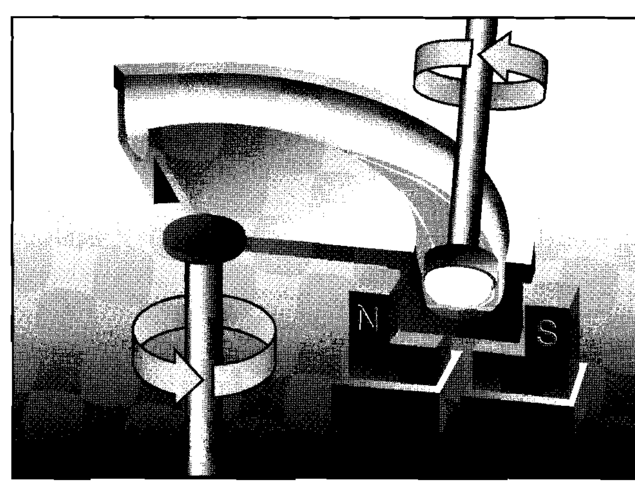

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Fig. 63.41
The MRF concept. A workpiece is immersed directly into the magnetorheological suspension for processing against a magnetic-field-stiffened, fluid lap.

polishing abrasives through the region of high pressure causes material removal at the workpiece surface. A key difference between the MRF process and that of Fig. 63.40 is that in MRF material removal takes place only in the vicinity of the small pressure spot rather than simultaneously over the whole surface of the workpiece. Other unique features of the MRF process are the controllable and conformal nature of the lap, the constant replenishment of the polishing zone with fresh suspension, and the continual removal of glass particles and heat generated in the polishing process.

A workpiece is polished by sweeping its surface through the zone of high pressure. Dwell time determines the amount of material that is removed. The illustration in Fig. 63.42 gives a cut-away view of the finishing process, where a spherical surface is shown in three orientations. The lens center is polished with the spindle normal to the bottom of the trough. Rotation of the spindle about the lens center of curvature causes annular regions of increasing diameter to come into the zone of high pressure for finishing. A key to the areal removal of subsurface damage, areal smoothing, and areal figure correction is the machine program that drives spindle motion at predetermined velocities through both positive and negative angles. Spherical or aspheric surfaces can be finished with the same machine setup, using customized machine programs.

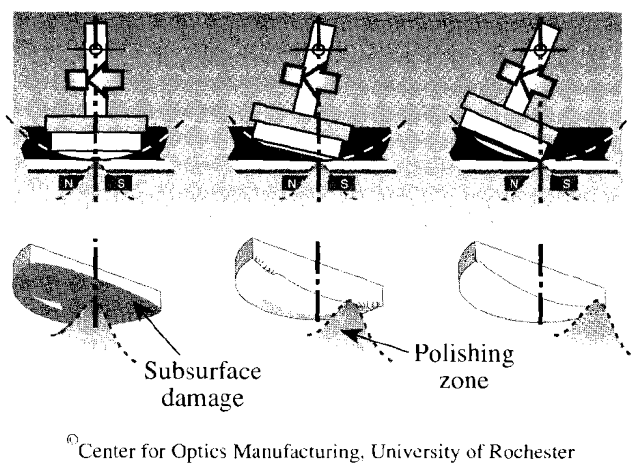

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Fig. 63.42
Polishing out a workpiece with the MRF process. Dwell time determines the ultimate surface shape and smoothness.

Magnetic Suspension, Polishing "Spot," and Parameter Studies

The MR suspension consists of noncolloidal magnetic particles, ~4.5 μm in diameter, mixed in an aqueous slurry with nonmagnetic polishing abrasives (see Fig. 63.43). When circulating suspension passes into the high magnetic field (~4 kG) created by an electromagnet, the magnetic particles form chain-like structures. The result is an increase in the viscosity and yield (shear) stress of the suspension by two orders of magnitude. A localized pressure spot is formed against the surface of the workpiece, and material removal occurs as a result of chemomechanical interactions.

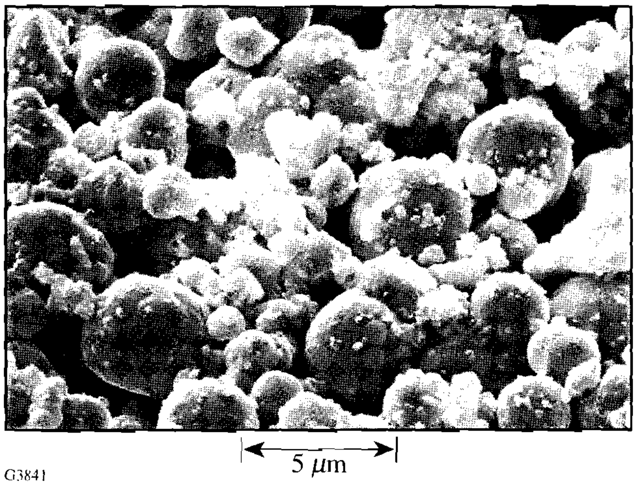

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Fig. 63.43
Scanning electron micrograph of an MR suspension containing 4.5-μm (initial median size) spherical magnetic particles and 3.5-μm (initial median size) CeO_2 particles. The sample was analyzed after one week of use.

The MRF removal function in the zone of high pressure is specific to the machine platform, the magnetic field strength, the workpiece geometry, and the properties of the material being finished. All experimental results reported in this paper were obtained on a pre-prototype MRF machine whose configuration resembles that shown in Fig. 63.41. Figure 63.44 shows the fluid flow direction and removal "spot" for a 40-mm-diam BK7 glass lens with an 84-mm radius of curvature, immersed in the MR suspension for 5 s. The spindle arm was oriented at an angle of $\theta = 2°$ and was locked to prevent workpiece rotation. Interferometrically derived depth profiles show that the removal function has a backward "D" shape, with a region of peak removal at the point of deepest penetration of the lens surface into the suspension. The peak removal rate is 4.6 μm/min, and the volumetric removal rate is 0.48 mm^3/min.

Several parameter studies have been conducted to evaluate the sensitivity of the polishing spot to process parameters. There is a significant dependence upon material type. Fig-

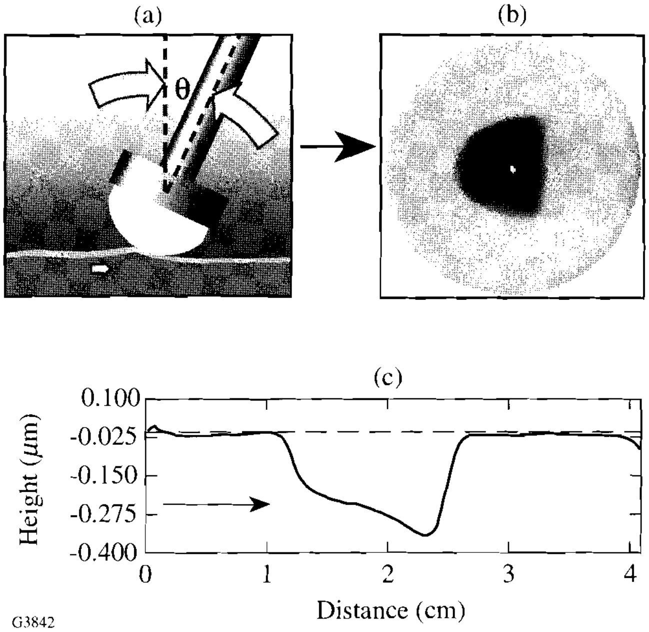


Fig. 63.44
MRF removal function on BK7 glass after 5 s. The "spot" areal size is approximately 2 × 2 cm for the conditions described in the text.

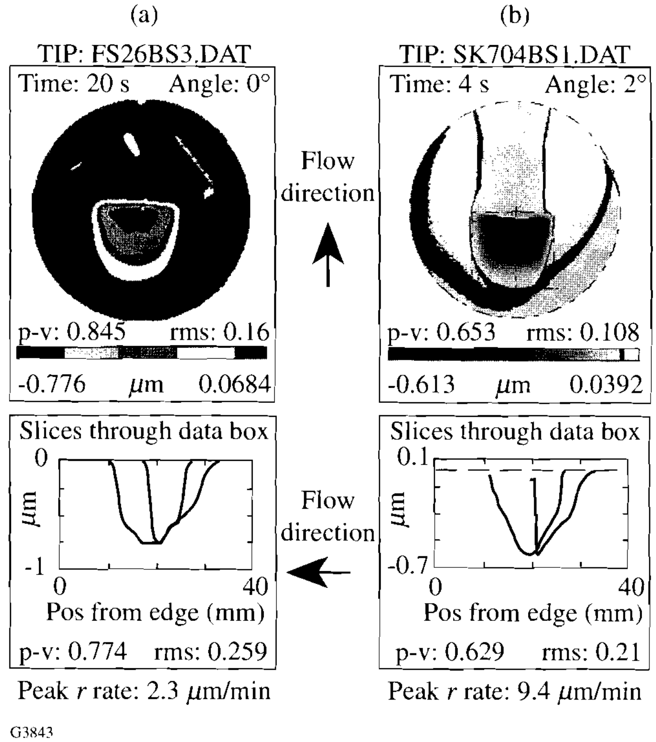


Fig. 63.45
Interferograms of removal "spots" for two different glass types under identical MR processing conditions. Depth-profile line scans shown below the spots are similar in shape.

ure 63.45 shows interferograms of spots taken on two different glass types. For the fused silica part, the spot is acquired by lowering the part into the suspension at normal incidence, turning the magnetic field on for 20 s, turning the field off, and raising the spindle-mounted part up and out of the suspension. Depth profile line scans, taken in orthogonal directions through the interferogram and displayed below the spot, give a peak removal rate of 2.3 µm/min for this glass. For the SK7 part, a spot is acquired by first turning on the magnetic field. The spindle-mounted part is then swept through an angle to the near-normal-incidence orientation in the suspension. It is kept there for a period of 4 s and then swept back out. Because of its composition and physical properties, SK7 polishes faster than fused silica. The measured peak removal rate is 9.4 µm/min. The spot shapes for these glasses are very similar. This is a characteristic of the MR process.

Figure 63.46 displays the peak and volumetric removal rates for a selection of seven optical glass types, measured under identical MR process conditions. There is a factor of nearly 4 increase in removal rate for F7 compared with fused silica (FS). The trend toward higher removal rates generally correlates with a decrease in silica content (change in chemistry of removal) and a drop in glass hardness (Knoop, Vickers, or lapping—change in mechanics of removal).

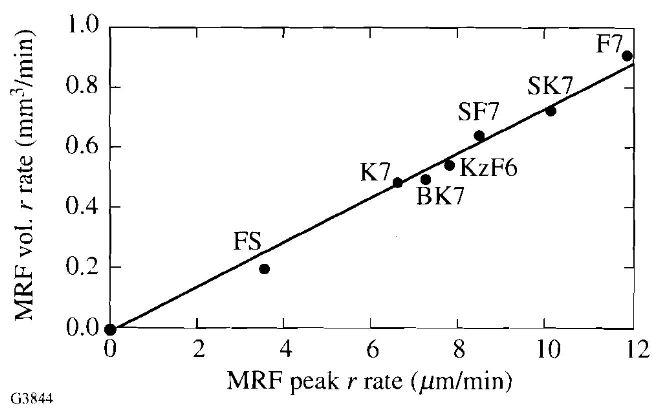


Fig. 63.46
Removal rates for several glass types under identical MR processing conditions. Softer glasses are generally seen to polish more rapidly.

Another parameter that has been studied is the sensitivity of final surface microroughness to glass type and to initial surface microroughness. Areal polishing experiments, conducted on spherical parts generated with deterministic grinding processes[8] at COM, show that the smoothing process is more sensitive to the initial condition of the surface than to the glass type. Figure 63.47 gives the time evolution of surface microroughness for the same set of seven optical glasses (40-mm diam), measured with two different types of optical profilers. Both sets of data show that the final rms surface microroughness, independent of glass type, is ~10 Å. If the initial rms surface microroughness is less than a few hundred angstroms, smoothing occurs in 5 to 10 min. The rate of smoothing drops for rougher surface conditions.

Deterministic MR Finishing of Convex Spherical and Aspheric Surfaces

Since 1993 a pre-prototype MRF machine has been used as a testbed for the development of software that enables technical personnel (not necessarily opticians) to deterministically finish optics.[9] The software is being developed for COM by Prof. Greg Forbes, Macquarie University, Sydney, Australia, and his graduate student, Mr. Paul Dumas of The Institute of Optics, University of Rochester. Most test parts for polishing experiments are prepared primarily on Opticam® CNC ring-tool generating machines at COM, although parts have also been provided by selected companies in the U.S. and elsewhere.

The Forbes/Dumas code requires three items as input: the shape and magnitude of the MRF removal function or "spot," the initial surface shape, and the processing objectives. The first item is obtained by generating a spot on a test piece of the same material type and shape to be finished. An interferogram of the removal spot, recorded by a Zygo Mark IV xp® interferometer, is acquired and loaded into the code. Alternatively, a previously recorded and stored spot profile may be called up from a database. The second input is the initial shape of the surface to be finished, which for a spherical surface is another interferogram showing initial deviation from a best-fit sphere. For an aspheric surface the input could be a surface profile obtained with a stylus instrument like the Rank Taylor Hobsen Form Talysurf®. The third input is the processing objective, which could be dc removal to eliminate subsurface damage, figure correction, or a combination of the two.

The Forbes/Dumas code runs on a PC. Using a series of complex algorithms, the code convolves the removal function with the initial surface shape to derive an operating program for the spindle-arm angular controller on the MRF machine. The code specifies angles and accelerations for the controller, the number of sweeps required between positive and negative angles, and the total estimated processing time. Finally, the code predicts the figure expected from the process cycle. The Forbes/Dumas code and the pre-prototype MRF machine controller are best understood with several examples.

1. Convex Spherical Parts from Fused Silica

One of several convex fused-silica parts (40-mm diam, 58-mm radius of curvature), generated on the Opticam® SX, was polished in three cycles to illustrate dc removal, figure correction, and surface smoothing. Results are given in Table 63.II. The first cycle lasted 32 min, removing 3 μm uniformly from the surface and reducing the areal surface roughness from 40 Å to 8 Å p-v (unfiltered, Zygo Maxim® 3D optical profiler). Symmetric surface wavefront error was held to an increase of 0.1 μm for 3 μm of material removed. (The configuration of MRF implemented in the pre-prototype machine does not permit efficient removal of any asymmetric features.) The second cycle (see below) brought figure error down from 0.42 μm to 0.14 μm. This was accomplished in 6 min with the (radially) selective removal of ~0.7 μm of material. A third cycle was implemented to remove an additional 3 μm of material while further reducing symmetric

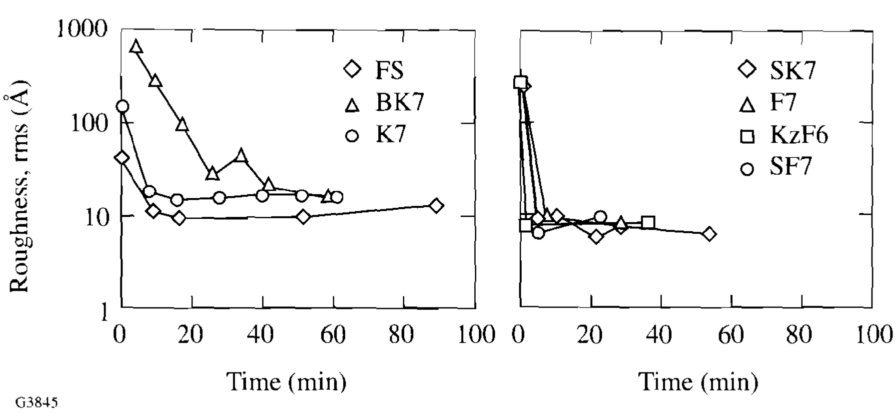


Fig. 63.47
Surface smoothing for a variety of 40-mm-diam glass parts with the same MRF process conditions. Final rms microroughness is ~10 Å. The smoothing time is 5–10 min for surfaces whose initial rms microroughness is under a few hundred angstroms.

figure error to 0.09 μm. The areal roughness remained at 8 Å rms. This is a good example of deterministic finishing.

A portion of the Forbes/Dumas user interface for cycle #2 is shown in Fig. 63.48. Interferograms for the initial, predicted, and actual surface-figure errors are shown at the top of the figure. Below each interferogram is a line scan (radial section) depicting the symmetric wavefront error compared with a best-fit sphere. This cycle removed a hole at the center of the surface.

2. Convex Spherical Parts from SK7 Glass

Other aspects of the interaction between the Forbes/Dumas code and the machine program are illustrated by the example given in Fig. 63.49. Here, a convex SK7 lens surface (40-mm diam, 58-mm radius of curvature) is processed in a figure

Table 63.II: Summary of results for MR finishing of a convex fused silica part in three process cycles.

Cycle	Amount removed (μm)	Duration (min)	Figure error* (μm p-v)	Areal roughness** (Å rms)
Initial	---	---	0.31	40
#1: dc removal/smoothing	3.0	32	0.42	8
#2: figure correction	0.7	6	0.14	7
#3: dc removal/figure correction	3.0	42	0.09	8
*Symmetric **0.25 mm², unfiltered				

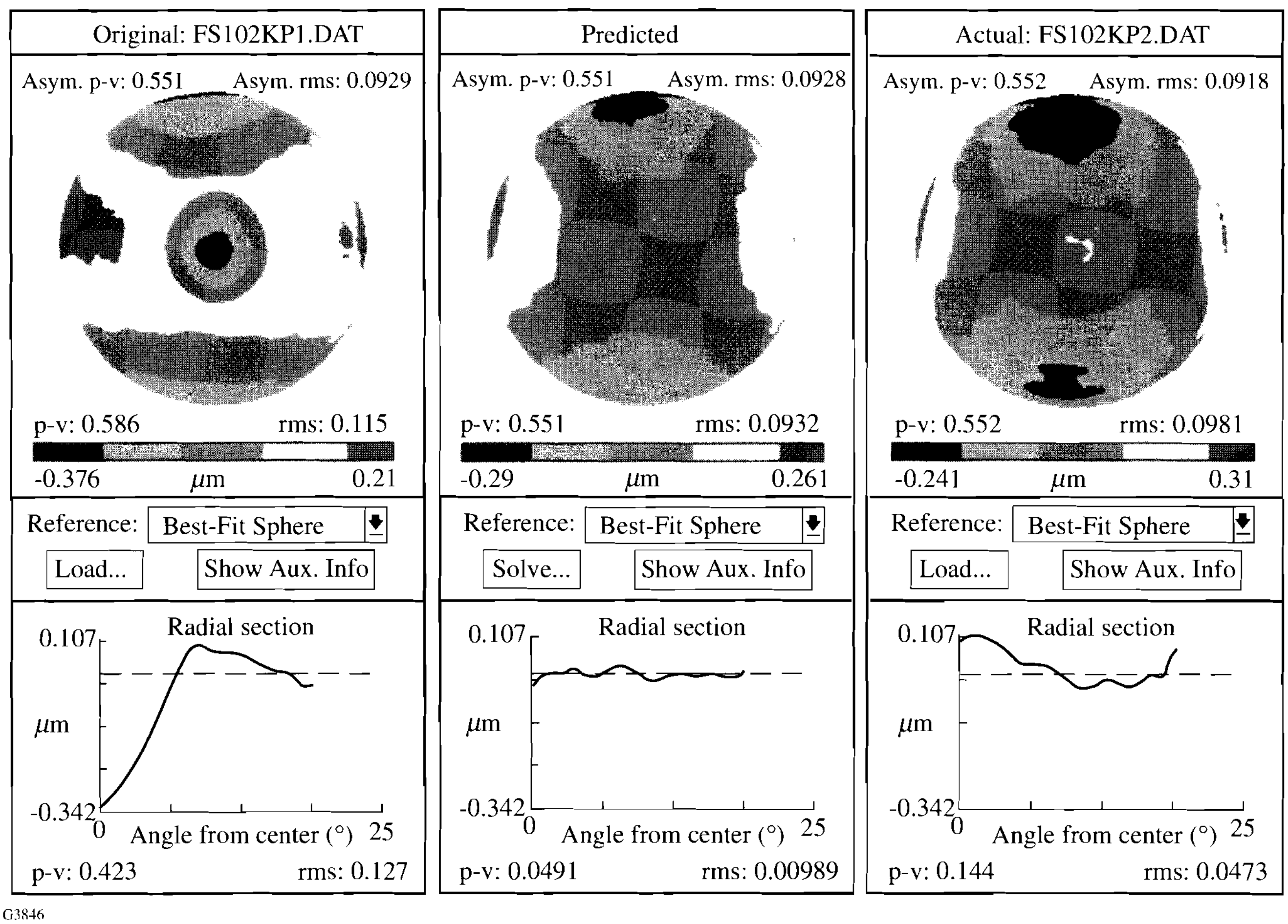


Fig. 63.48
Initial, predicted, and actual results for a ~6-min figure-correction cycle. The central hole was removed.

correction cycle. The left column shows a (symmetric) radial section of the initial surface, indicating a hill or bump in the part relative to the best-fit sphere. Directly below is a (symmetric) radial removal contour, calculated by the code, for correcting the figure error. It indicates that approximately 0.6 μm of material must be removed, primarily at the center of the part, in order to reduce the p-v wavefront error (0.334 μm) to that shown in the prediction at the top of the middle column (0.052 μm). The machine control program required to perform this operation is shown graphically at the bottom of the middle column. The curve indicates the angular velocities (1 mrfs = 0.01°/s) to be programmed into the MRF machine spindle controller for one sweep of the part through the suspension. Information is provided at the bottom of the right column on the duration of the correction run (1.2 min) and the number of angular sweeps or scans (2). Actual results from this cycle are shown at the top of the right column. Results (0.07 μm) agree well with the prediction, both in amplitude and shape. This is another good example of deterministic finishing with MRF.

3. Asphere Polishing Experiment

COM and Texas Instruments (TI) are collaborating to demonstrate deterministic manufacturing of aspheric optical elements. In a recent experiment ten BK7 lenses were manufactured using the Opticam® SM at TI for generating and the pre-prototype MRF machine at the COM for finishing. The test parts were plano-convex aspheres (hyperboloids), 47 mm in diameter, with 140 μm of aspheric departure (see Fig. 63.50). The aspheric surface figure requirement was 0.93 μm p-v, with a 0.1% tolerance on base radius. Machined parts received at COM had residual form errors ranging from 4 μm to 20 μm p-v. Initial surface roughness values were as high as 10,000 Å rms.

Finishing the parts to final figure was accomplished in two MRF cycles. Subsurface damage was removed and smoothing was performed in the first cycle. Remaining figure errors were usually corrected in a second cycle. Results for one lens are given in Fig. 63.51. Process conditions/results for each cycle

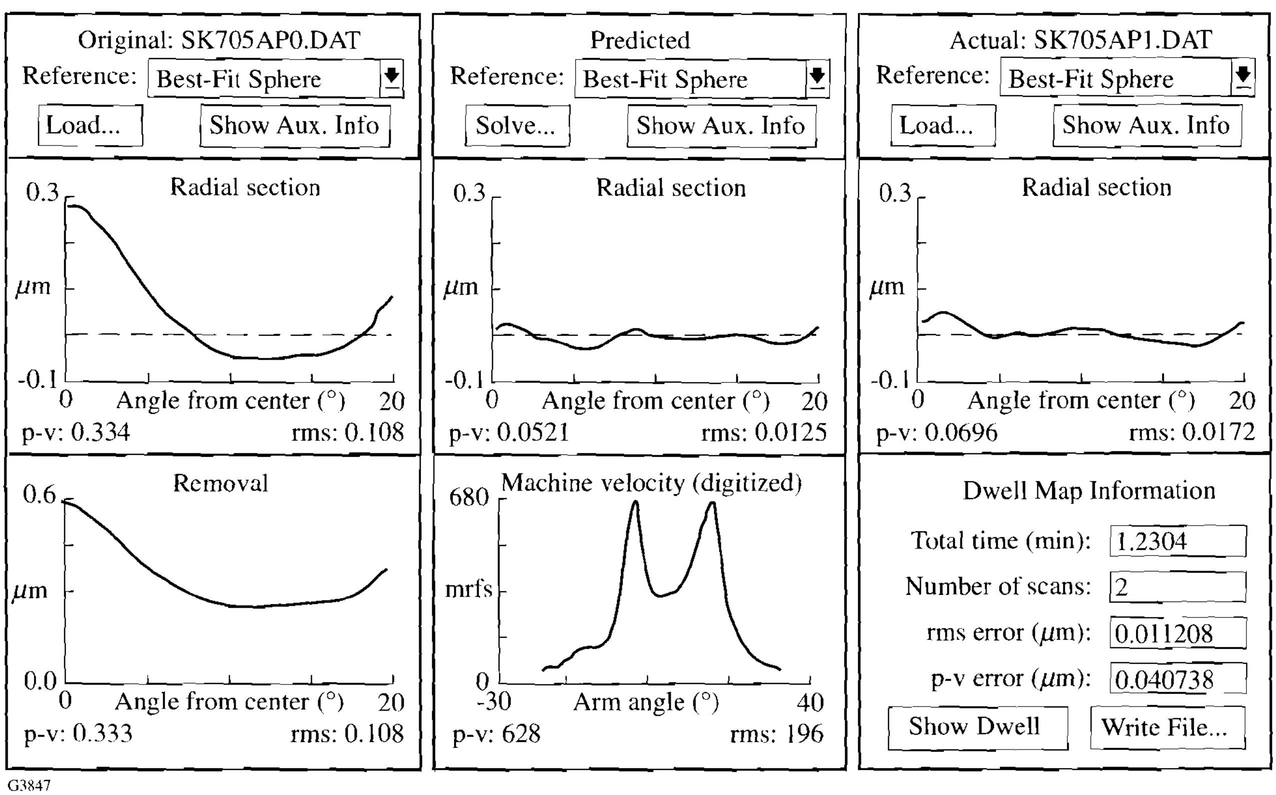
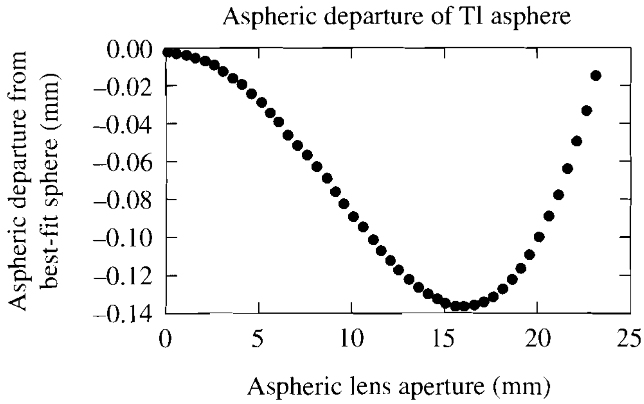


Fig. 63.49
Details of Forbes/Dumas code for spherical figure correction. An MRF machine control program is generated along with the prediction for surface shape errors. After a 1.2-min running cycle, the actual p-v figure error of 0.07 μm shows excellent agreement with the prediction of 0.05 μm, both in form and amplitude.

are indicated on the left and relevant Form Talysurf® scans on the right. In the first MRF cycle, 12 μm of material were removed over a period of 100 min. The rms roughness was reduced from 9400 Å to 10 Å. All subsurface damage was eliminated. (HF acid etching on identical parts confirms that MRF does not introduce new subsurface damage.) The second figure correction run required 40 min of polishing time; 4 μm of material were removed. At the conclusion of this cycle the form error was reduced to 0.86 μm. These BK7 lenses were returned to TI and judged acceptable for inclusion in a breadboard of their deformable mirror device assembly, an integral part of TI's digital imaging technology.



- BK7 glass diameter: 47 mm
- Design radius of curvature: 70 mm
- Conic constant (k): –8.034

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Fig. 63.50
Aspheric shape required for a collaborative deterministic manufacturing experiment with Texas Instruments.

Summary

MRF is a promising new optics manufacturing technology. Fundamental to this technology is an environmentally safe, aqueous suspension of magnetic particles and polishing abrasives, whose viscosity is increased by orders of magnitude in a magnetic field. The stiffened suspension acts as a "spot" lap that conforms to and polishes out the surface of a workpiece immersed in it. In initial trials on a pre-prototype machine, MRF has shown an excellent capability for smoothing ground glass surfaces, correcting figure errors, and eliminating subsurface damage. Experiments have demonstrated that, with machine-control programs generated by a computer algorithm, both spheres and aspheres can be finished with the same machine setup, for a variety of optical glasses.

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Cycle	Amount removed (μm)	Cycle time (min)	rms* roughness (Å)	p-v fig. (μm)
Initial	---	---	9400	6.42
#1: dc ssd removal/ smoothing	12	100	10	4.40
#2: figure correction	4	40	10	0.86

*Zygo New View®, 20x Mirau

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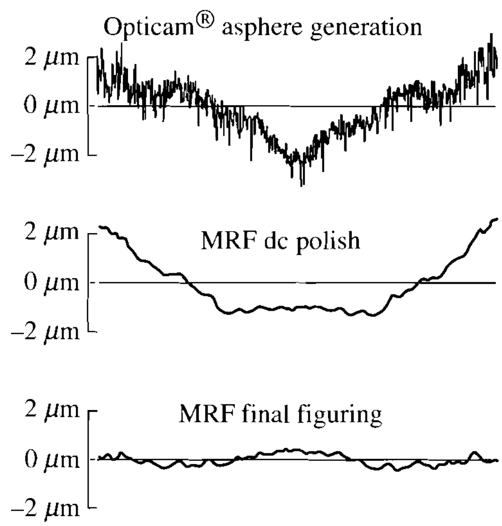

Fig. 63.51
Finishing of a 47-mm-diam asphere in two MR processing cycles. The entire polishing and figuring operation required 140 min of machine time.

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