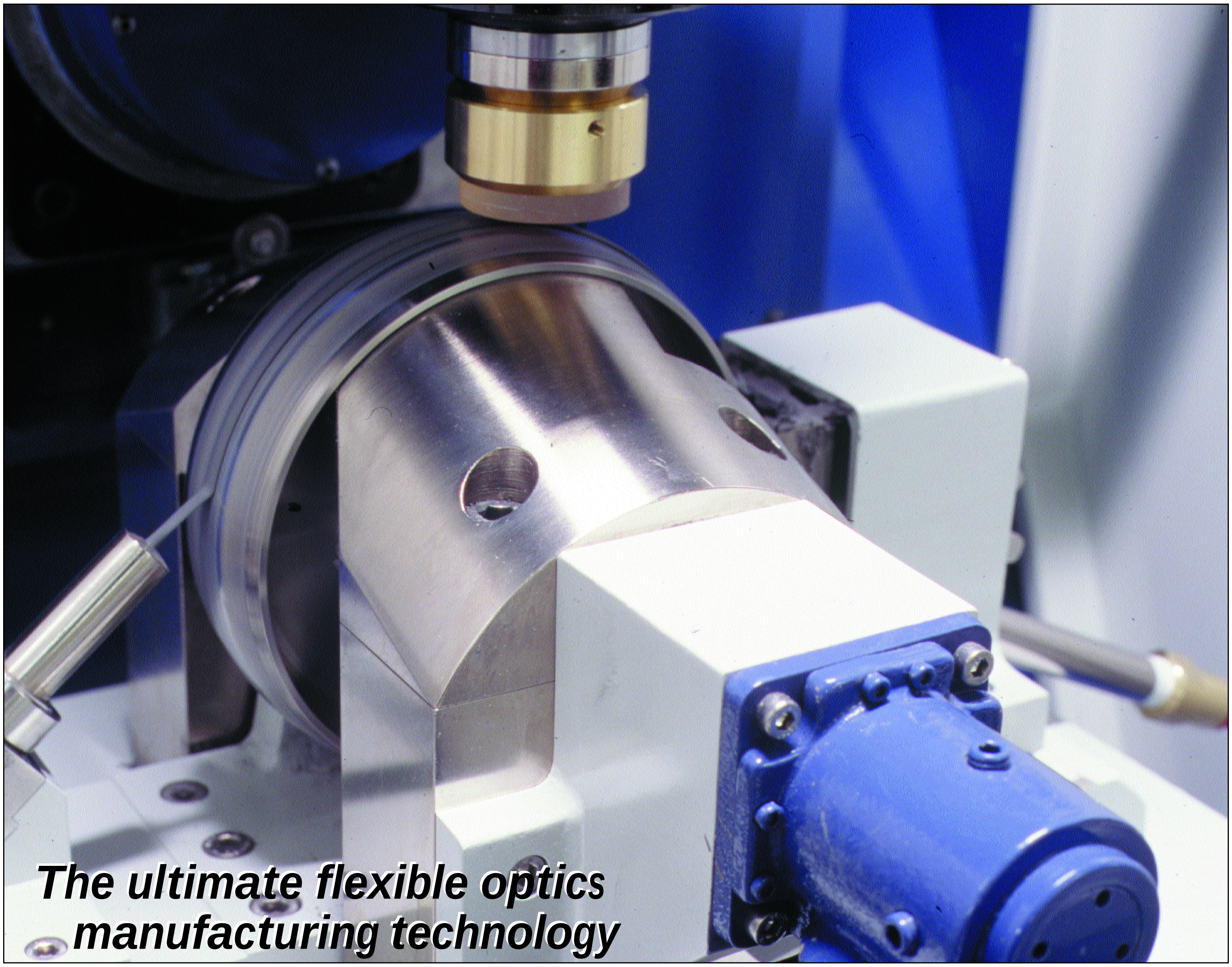
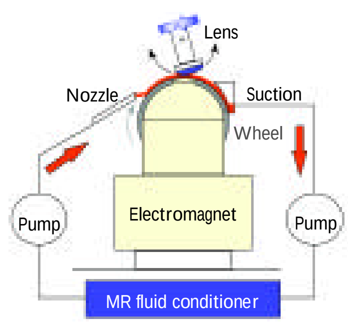


Photocourtesy of QED Technologies.

Magnetorheological Finishing

DON GOLINI, GUNTER SCHNEIDER, PETER FLUG, and MIKE DeMARCO

A revolutionary precision polishing method called magnetorheological finishing (MRF) has been developed to overcome many of the fundamental limitations of traditional polishing techniques. MRF is a deterministic subaperture process that has a demonstrated ability to finish spherical and plano surfaces to an accuracy of better than 30 nm peak to valley and surface microroughness less than 1 nm on optical glasses, single crystals, and glass ceramics.



Schematic of the magnetorheological finishing unit.

The MRF process uses magnetorheological (MR) fluid as a polishing tool. To carry out the polishing operation, a workpiece is installed at a fixed distance from a spherical wheel that rotates about its horizontal axis. An electromagnet located below the wheel surface generates a gradient magnetic field in the gap between the wheel and the workpiece. An MR fluid is delivered to the rotating wheel, pulled against the wheel surface by the magnetic field gradient, acquires the wheel velocity, develops high stresses when it contacts the workpiece, and becomes a subaperture polishing tool. The removal rate of the polishing tool correlates with the viscosity of the MR fluid, which is controlled in situ to +/- 1%. A sophisticated computer program determines a schedule for varying the position of the rotating workpiece through the polishing zone.

The extreme stability of the polishing tool, coupled with nearly infinite compliance to an aspheric workpiece, makes the MRF technology a breakthrough in deterministic polishing of precision spheres, flats and aspheres.

Despite the fact that QED Technologies (Rochester, New York) has deployed more than 50 MRF machines onto factory floors all over the world, many people continue to associate MRF exclusively with polishing aspheric lenses or ultraprecise photolithography lenses. While these are the two most common uses of MRF, they are hardly the only ones.

In many of the world's optics shops today, the most common production requirements are for low and medium volumes (batches of 1-50 components) with figure requirements between 1 and 1/10 fringe peak to valley (p-v). Although modern computer numerically controlled (CNC) optics production lines can meet these requirements, doing so typically entails relatively time-consuming and complex machine setups requiring experienced operators and dedicated tooling. For a typical small batch job, it can take hours to prepare the equipment necessary to perform a few minutes of production work.

Coupling advanced CNC optics manufacturing equipment with the flexibility and simplicity of MRF technology provides a compelling alternative for normal optics production. Once the MRF system is integrated into the CNC line, small-, medium- and large-batch lens production can be accomplished with minimal set-up and dedicated tooling. MRF also enables a host of other opportunities, including the ability to fabricate aspheres, ultrahigh precision optics, thin waferlike substrates, and even rectangular optics such as prisms and cylinders.

Normal optics production

MRF offers tremendous advantages for normal optics production. For example, consider a concave-convex lens, radius 60 mm, diameter 80 mm, and center thickness 8 mm. The production line required to polish the convex side of this lens with CNC polyurethane polishing based equipment should consist of a generating machine and two (see Table 1) or three polishing machines. The reason for this combination is that the polishing to achieve a final quality requirement of 1/4 fringe takes approximately three times longer than the generating. Therefore, one generator is paired with multiple polishers to maintain constant throughput.

It is clear from Table 1 that this approach is more cost effective for larger volume batch sizes than for more common batch sizes of tens of units. The difficulty with respect to small batches stems from two basic conditions.First, when using CNC technology for lower precision

		# of Units	500	100	10
	Setup Time (min)	**Cycle Time** (min)	**Total Time** (min)		
Generating Machine	20	3	1500	300	30
Polisher #1	180	9	2250	450	90
Polisher #2	60	9	2250	450	0
		Total Job Elapsed Time (min)	2510	710	290
		Average Time per Lens	5.0	7.1	29.0

Table 1. Typical CNC optics manufacturing line for producing 1/4 fringe p-v optics.

		# of Units	500	100	10
	Setup Time (min)	**Cycle Time** (min)	**Total Time** (min)		
Generating Machine	20	3	1500	300	30
Polisher #1	30	3	1500	300	30
MRF	30	3	1500	300	30
		Total Job Elapsed Time (min)	1580	380	110
		Average Time per Lens	3.2	3.8	11.0

Table 2. CNC optics manufacturing line for producing 1/4 fringe p-v optics incorporating MRF.

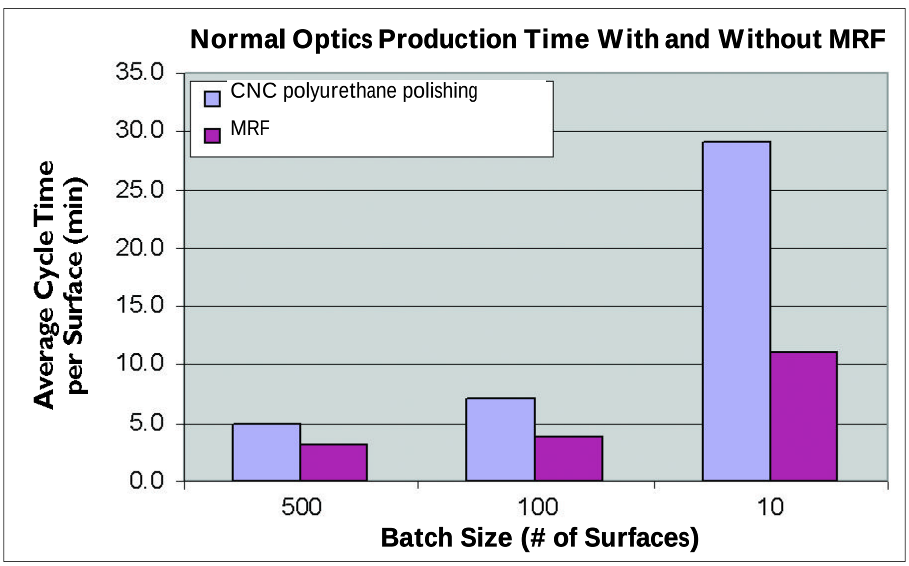


Figure 1. Comparison of a CNC polyurethane polishing line versus MRF-based production line for precision optics in various quantities.

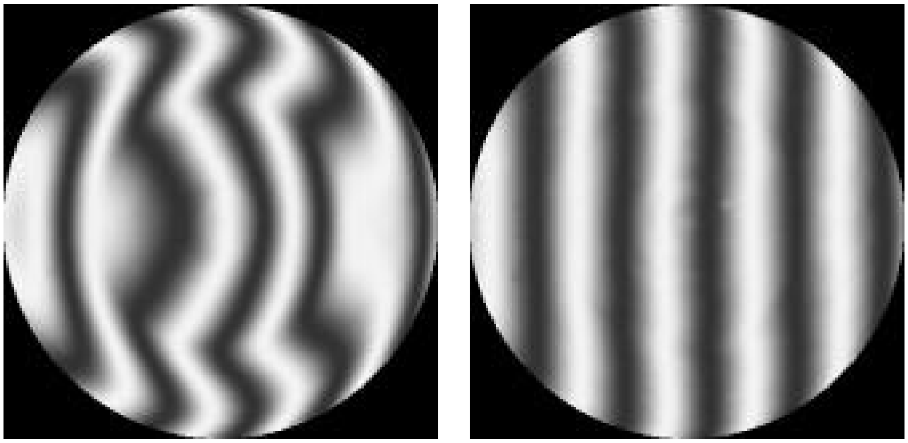


Figure 2. Interferograms of a 30-mm-diameter spherical lens after conventional polishing,and then after a two-minute polishing run with MRF. (*Source QED Technologies*.)

Figure 3. A typical optical window with a high aspect ratio. (*Photo courtesy of QED Technologies.)*

optics,setup can be very quick (on the order of a half hour). However, it can take three or four hours to set up a polishing machine to polish a lens to 1/4 fringe or better using CNC polyurethane polishing. The most time-consuming setup on the polisher is to bring a lens from 1 fringe to 1/4 fringe,particularly for thin lenses. Second, cycle-time is compromised significantly when working to high precision, since to avoid process instabilities, less aggressive polishing parameters must be applied for pressure and velocity. This results in higher unit cost for lower volumes.

Compare the example in Table 2, which is similar to the example in Table 1 except that one of the two CNC polishers has been replaced with one MRF machine. The potential for this combination may not be immediately obvious, but the deterministic MRF technology actually relaxes and alleviates many of the requirements of the previous polishing steps in the process.

Notice the polyurethane polishing setup time has been reduced from three hours to 1/2 hour, because it is far easier to set up a CNC polyurethane polishing machine to produce two-fringe p-v optics than to produce 1/4 fringe optics. Furthermore, the CNC polyurethane polishing time has been reduced to three minutes because higher speeds and pressures are permissible when producing two-fringe optics. And why is it acceptable to set up the CNC polyurethane polisher to produce only two-fringe optics when 1/4 fringe optics are required in the end? Because the MRF system at the end of the line is easily capable of correcting a typical two-fringe p-v global error to 1/4 fringe in a matter of *minutes* (Figure 2). An operator would interferometrically measure the lens after polyurethane polishing, and feed the data map into the MRF system over a network connection. At this point, the MRF machine would go to work. In fact, the CNC polisher can be stable enough that the error on each lens is quite repeatable;therefore, depending on the final figure requirement, metrology may be performed on every fifth or tenth lens prior to MRF.

Figure 1 is a comparison of these two production-line scenarios. The graph shows that when MRF is used, sensitivity to volume diminishes significantly, and in all cases, the cycle time is better with MRF. This is due to decreased setup time and cycle time for each polishing step.

There are many additional hidden cost advantages. The skill level of the operator on the CNC polyurethane polisher can be significantly lower because of the relaxed figure requirement. None of the steps require sophisticated dedicated tooling, so tooling inventory and costs are low, and the system offers tremendous flexibility from job to job. In fact, modern CNC polyurethane polishing machines include an integrated tool correction capability to easily enable radius correction and faster machine setup. In an industry that has come to accept poor yields and ever-changing production schedules, the MRF system improves yields dramatically, providing stable, predictable manufacturing flow. This model presents a compelling case for using MRF in normal optics shops for normal optics. However, the MRF line can do far more than produce normal optics.

Magnetorheological finishing

MRF, a deterministic subaperture finishing process, has significant fundamental advantages over CNC polyurethane polishing. It uses a magnetorheological polishing fluid to preferentially polish based on dwell time. Workpiece surface errors are characterized and deconvolved with an interferometrically determined removal function to create dwell-time instructions for the process. The removal function is extremely stable because removal rate correlates with fluid viscosity, which is continuously monitored and controlled to $\pm 1\%$. The MRF fluid forms a polishing tool (approximately one square centimeter) that is perfectly conformal and capable of polishing high-precision spheres and flats, aspheres, optical surfaces with square or rectangular apertures, prisms, and even cylindrical optics.

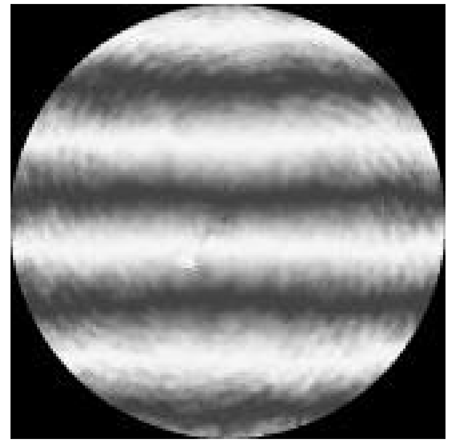
From the practical standpoint of a typical optics shop, the automation and flexibility of the MRF process is most compelling. Because the re-circulated polishing tool never dulls or changes, the process simulation is extremely accurate, and the typical machine operator can become proficient in its use in a matter of weeks. There is little to no dedicated tooling required, so changing from one job to another is quick and straightforward. Furthermore, in many cases the process may be optimized at the touch of a button. For example, removal may be increased or decreased by varying the magnetic field,the polishing wheel velocity or the depth into the polishing fluid. Excellent results are achieved on most materials, including optical glasses, fused silica and calcium fluoride.

High aspect ratio optics

Some of the most difficult jobs in the optics shop involve optics with a diameter that is significantly larger than its thickness (greater than 15:1). The difficulty of polishing high aspect ratio optics lies in the fact that since they are mechanically flexible on an optical scale, when mounted for polishing, they are often inadvertently stressed. For example, a thin plano window (Fig. 3) is typically mounted to a rigid base and polished extremely flat. Upon removing the window from the mount, it returns to its stress-free state and is no longer flat, since glass is perfectly elastic. This is particularly troublesome when working to requirements of better than 1/2 fringe p-v. MRF is insensitive to mounting distortion or deformation during polishing. The reason is that the removal function is not very sensitive to the depth the lens is immersed into the fluid, provided the depth variation is on the order of a typical mounting distortion (a few micrometers). With MRF, the critical element of the process is the metrology, i.e.,metrology must be taken in the stress-free or as-used condition. The metrology is then fed into the MRF system, which uses the subaperture tool to preferentially polish the mapped high zones (as determined by the metrology), regardless of mounting distortion.

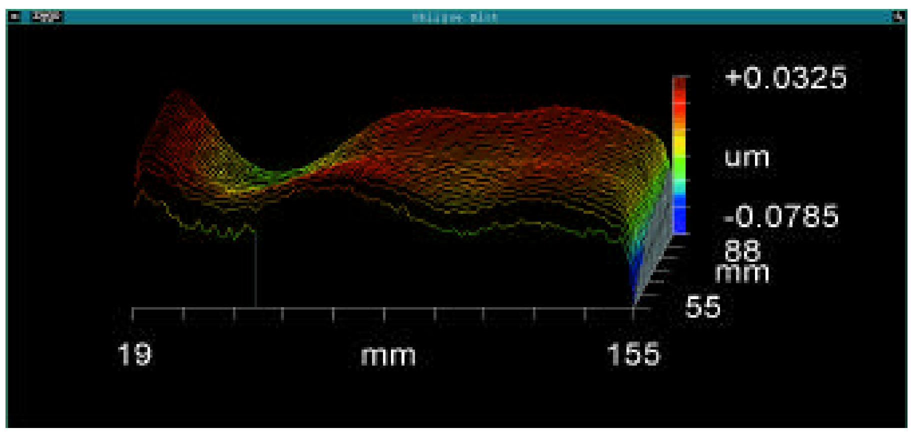
This powerful MRF capability may be used to polish thin lenses, thin optical windows such as thin-film filter substrates for telecommunications, or even wafers used in microelectronic applications. And the metrology may represent anything ranging from surface flatness, to transmitted wave front, to total thickness variation (TTV) or even optical thickness (mechanical plus optical path thickness). A key property of MRF is that is can precisely polish a nonflat shape as easily as it can polish a perfectly flat shape. This is very useful for applications such as polishing windows to correct for material inhomogeneity, phase plates for laser beam correction, or even correcting misalignments found in multi-element optical systems after assembly by polishing the system correction into the outermost surface and reassembling.

Ground on Schneider ALG 200

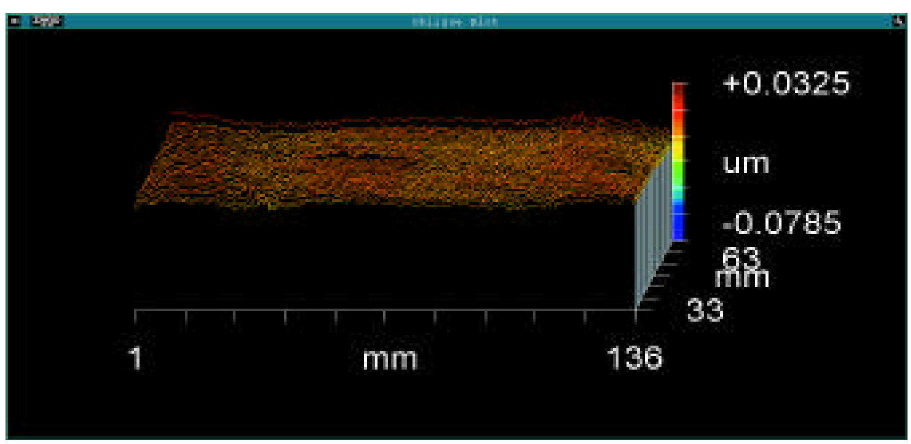


Polished on Q22 MRF system

Figure 4. An example of an aspheric lens surface with 400 μm of departure, tested with a computer-generated hologram (CGH), produced on the Schneider ALG 200 and the QED Q22 MRF system in 30 minutes.



p-v 0.296λ



p-v 0.038λ

Figure 5. An example of the capability of the MRF raster tool to improve the figure of a Zerodur bar (130 mm x 30 mm) from λ/3 to λ/25 p-v.

Aspheres

Aspheric optics provide significant advantages, including improved optical performance (reduced aberrations), increased transmission, reduced package size, weight, and volume, and lower material costs (one asphere replaces two or more spherical optics). Because of these significant advantages, aspheres are to be found in every application for which they can be manufactured. Nearly every newly designed infrared (IR) military system uses aspheres because of the maturity and pervasiveness of diamond turning, and most high-volume optical consumer products on the market today use glass or plastic *molded* aspheric lenses.

While manufacturing techniques exist for IR and high-volume consumer optics, most optics manufacturing technologies for high-precision visible aspheric optics are extremely expensive. QED Technologies (Rochester, New York) and Schneider Optical Machinery (Steffenberg, Germany) have teamed to develop a turnkey production-ready solution for asphere manufacturing to enable glass aspheres to become a cost effective and reliable alternative to spherical optics in low- and medium-volume, high-precision applications (Fig. 4).

Prisms with the raster version

The most recent implementation of MRF technology enables polishing square or rectangular mirrors and windows, prisms, and even cylindrical optics by using a raster tool path.

Working the edges of non-round components using conventional polishing techniques presents a significant challenge, because the polishing tool performance near the edges and corners of the optic is unpredictable and often severely degrades flatness.

By raster scanning, instead of rotating the workpiece, a high-convergence MRF tool has been developed to perform fine figure and angle correction on prisms (Fig. 5). The raster-scan machine uses a five-axis CNC platform, a new software engine, and advanced algorithms.

Summary

Before the introduction of advanced CNC technology, normal optics production was a highly labor- and skill-intensive process.

Even today, all over the world hand grinding and polishing are the most common optics production techniques. But more and more smaller companies are enjoying the benefits that automation has to offer.

Capital-intensive approaches level the playing field for optics manufacturers of all sizes. As lot sizes go down from tens of thousands to hundreds or tens of units per month, and precision requirements go up, with shops commonly needing to produce 1/4 fringe optics, CNC equipment combined with MRF can get the job done faster, with less tooling and lower skill levels than traditional manual approaches.

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